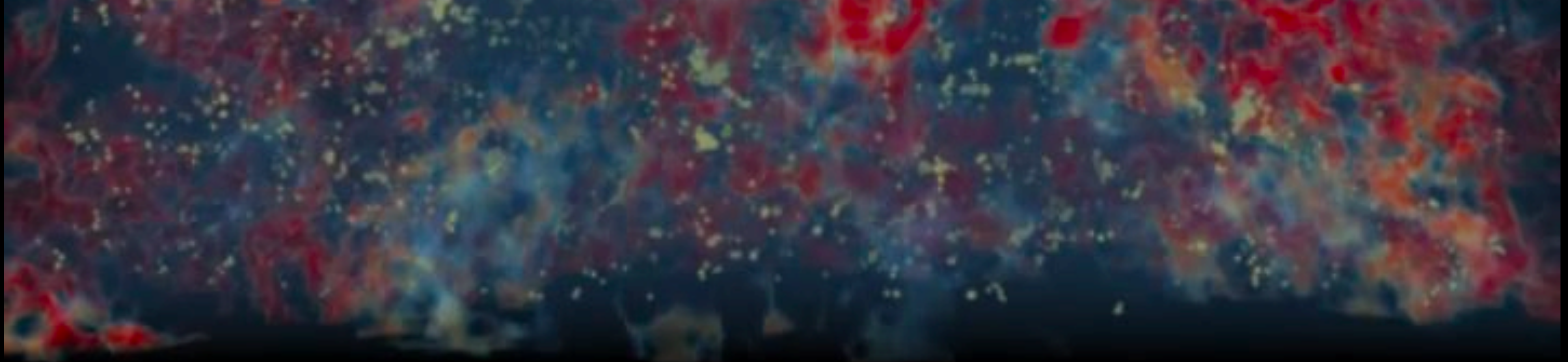


The Hydrogen Epoch of Reionization Array (HERA)

Aaron Ewall-Wice

NPP Fellow,
Jet Propulsion Laboratory, California Institute of Technology.

On behalf of The HERA Team

<u>17 Institutions:</u> UCB, MIT, SNS, UPenn, NRAO, UCLA, QMUL, ASU, UW, Brown, Cambridge, SKA-SA, Cal Poly Pomona, UKZN, UWC, McGill, JPL

55 Active Collaborators

Excellent Slack Channel to collaborator ratio (1:1)

On behalf of The HERA Team

Aaron Parsons (PI)
Zuhra Abdurashidova
James Aguirre
Gianni Bernardi
Judd Bowman
Rich Bradley
Phil Bull
Chris Carilli
Cherie Day
Dave DeBoer
Eloy de Lera Acedo
Steve Furlanetto
Brian Glendenning
Bryna Hazelton
Jacqueline Hewitt
Jack Hickish
Danny Jacobs
Adrian Liu
David Moore

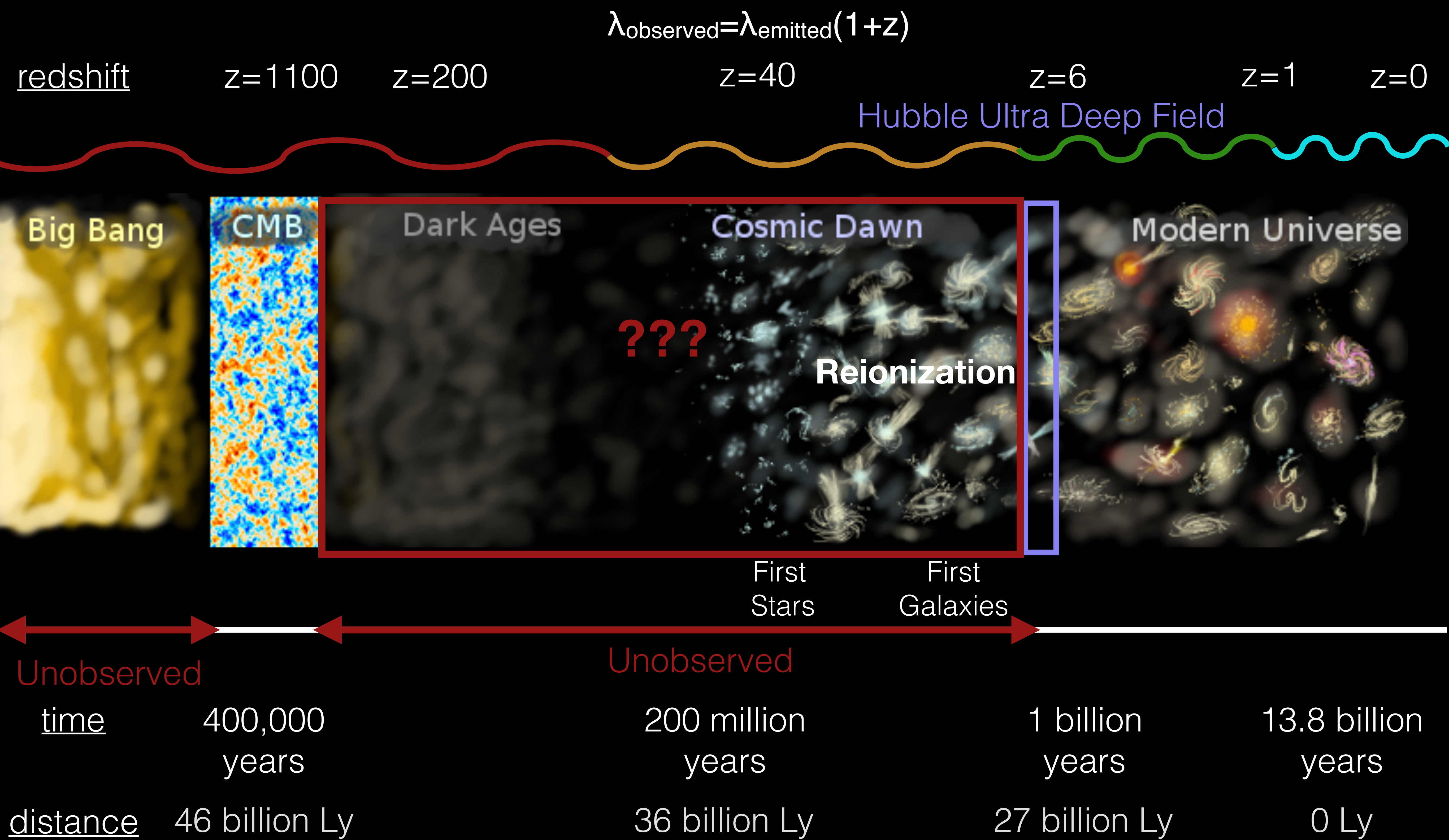
Dave MacMahon
Andrei Mesinger
Miguel Morales
Jonathan Pober
Nima Razavi-Ghods
Daniel Riley
Kathryn Rosie
Alexander Rudolph
Mario Santos
Jon Sievers
Ian Sullivan
Max Tegmark
Dan Werthimer
Peter Williams
Adam Beardsley
Josh Dillon
Bradley Greig
Zaki Ali
Saul Kohn
Abraham Neben

Matt Kolopanis
Paul La Plante
Juan Mena Parra
Jordan Mirocha
Steven Murray
Ridhima Nunhokee
Nipanjana Patra
Nithyanandan Thyagarajan
Nichole Barry
Jacob Burba
Ruby Byrne
Carina Cheng
Nic Fagnoni
Deepthi Gorthi
Nick Kern
Josh Kerrigan
Adam Lanman
Victor Li
Wenyang Li
Zak Martinot
Honggeun Kim

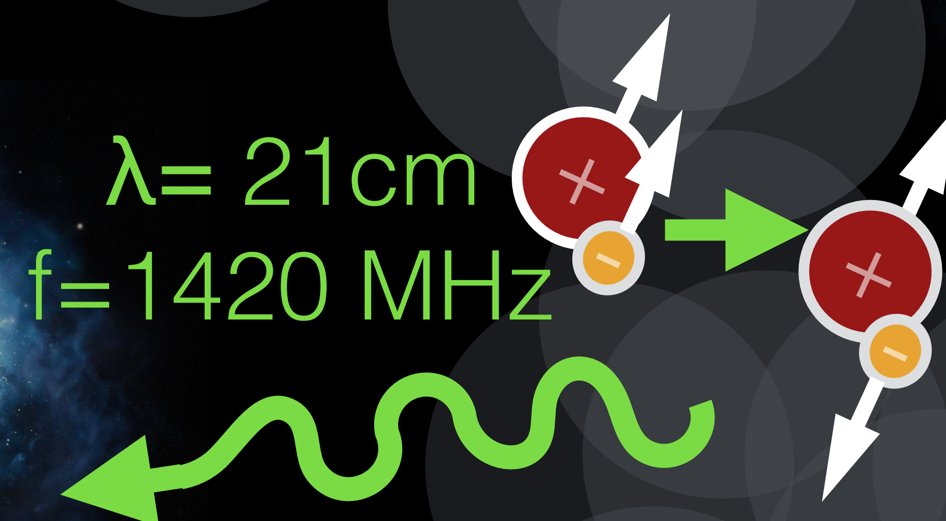
Outline

- 21-cm Cosmology and the Cosmic Dawn — What can we learn?
- Foregrounds and Systematics — How the HERA collaboration is addressing them.

We are using 21 cm to fill in our cosmic timeline.

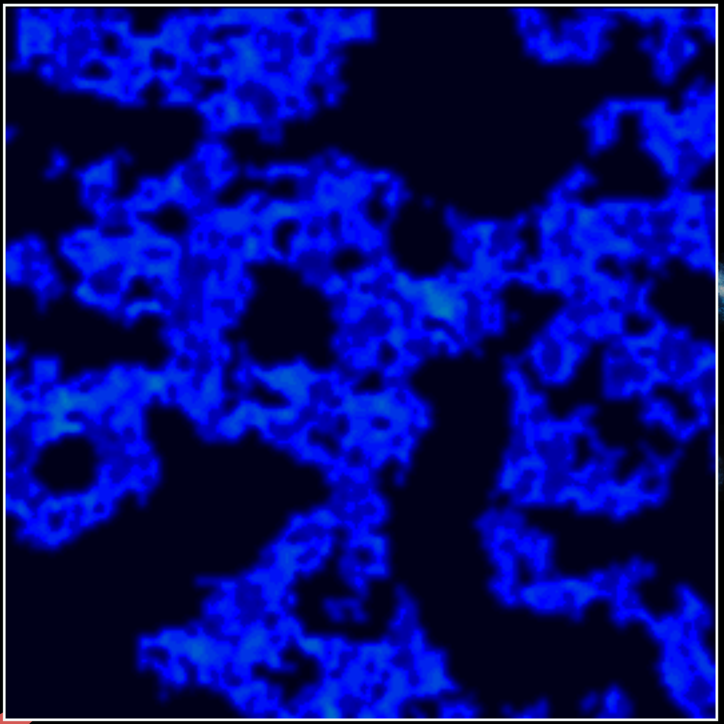


21cm Tomography
Lets us Observe the Impact of the first Galaxies on Intergalactic Gas



21cm Tomography

$\lambda = 1.68$m
f=158 MHz

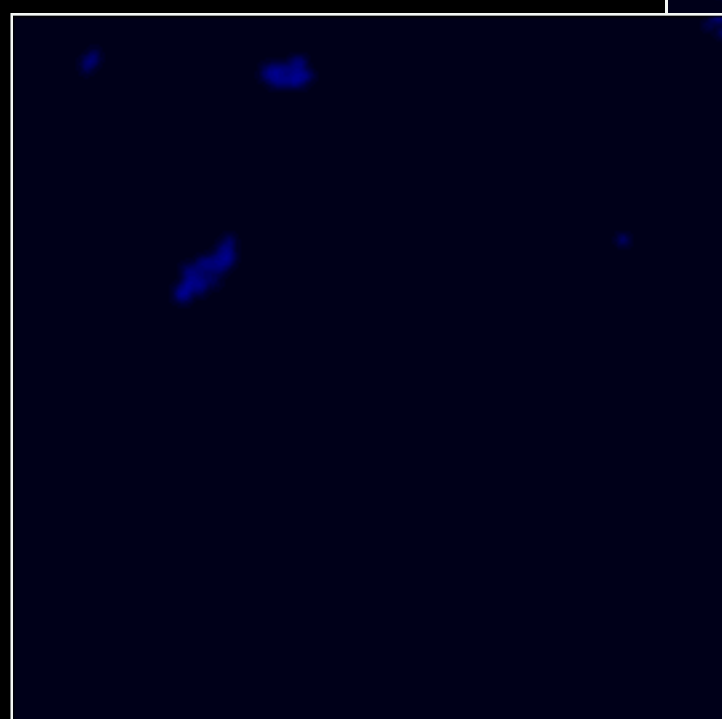


z = 8

Mesinger 2011

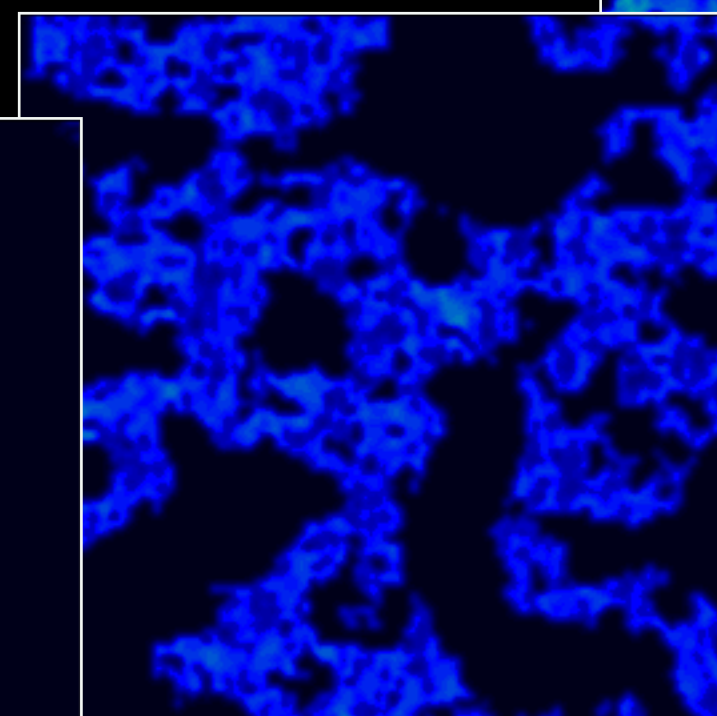
21cm Tomography

λ= 1.47 m
f=202 MHz



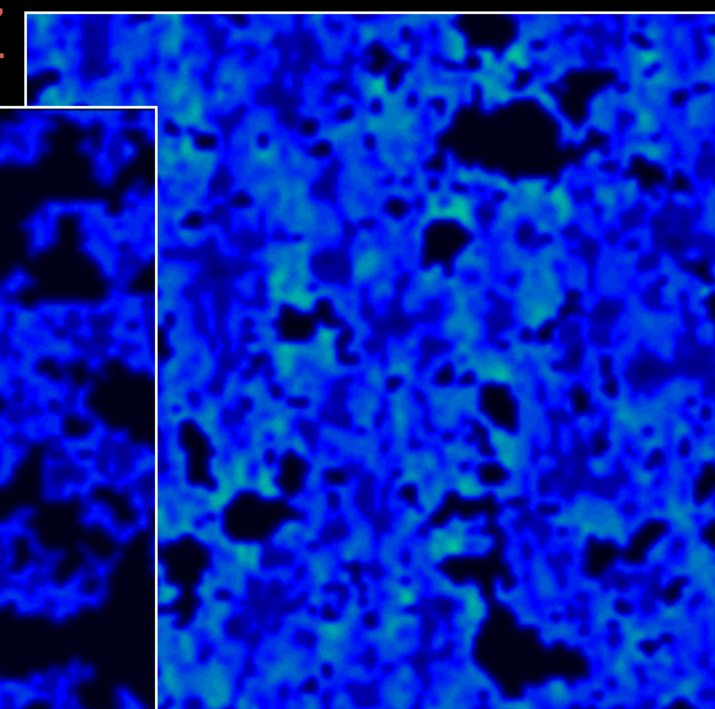
z = 6

λ= 1.68m
f=158 MHz



z = 8

λ= 2.1m
f=130 MHz

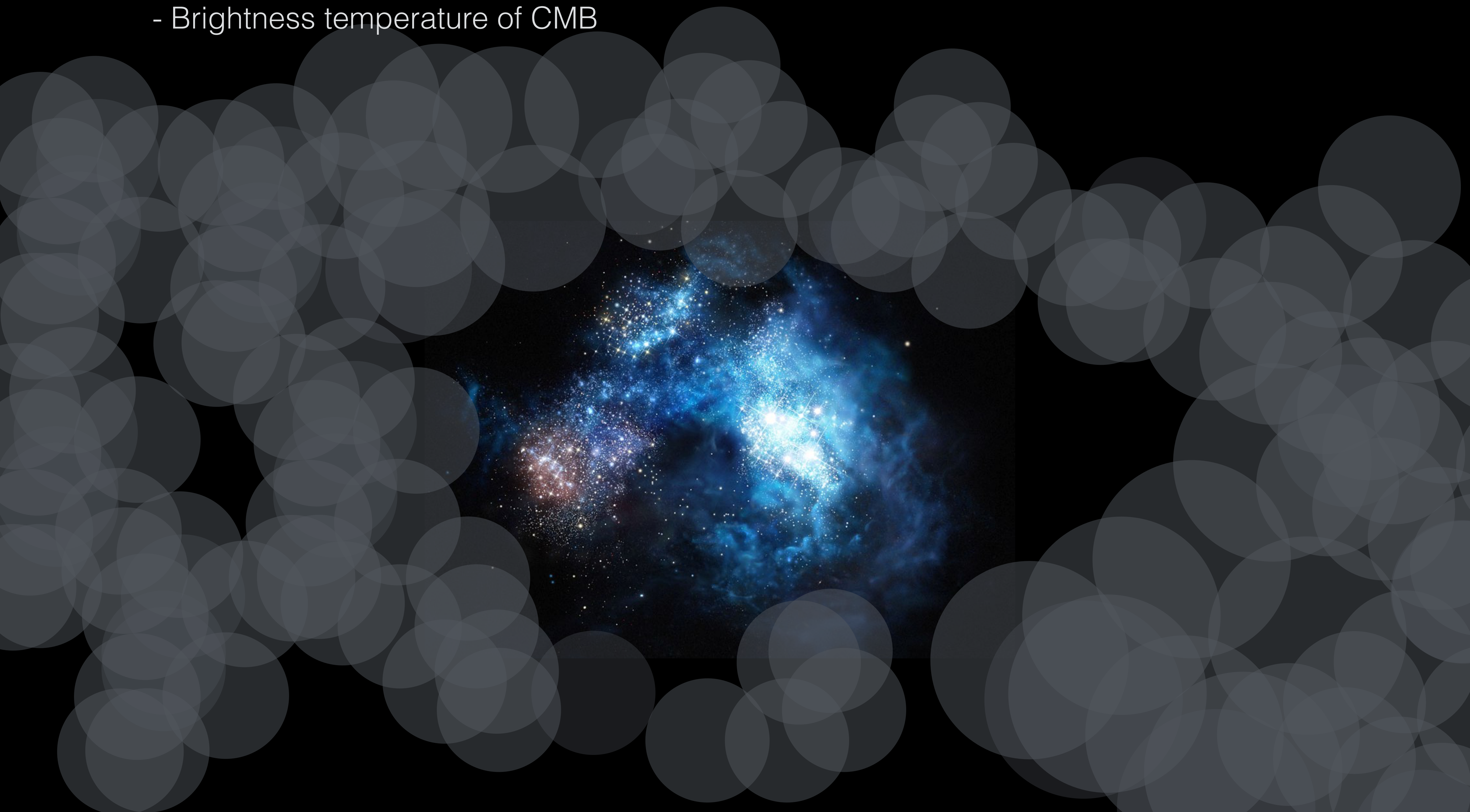


z = 10

Mesinger 2011

How Astrophysics Affects 21cm Emission

δT_b =Differential Brightness Temperature
= Brightness temperature of 21cm
- Brightness temperature of CMB



How Astrophysics Affects 21cm Emission

δT_b =Differential Brightness Temperature
= Brightness temperature of 21cm
- Brightness temperature of CMB

Temperature of cosmic microwave background

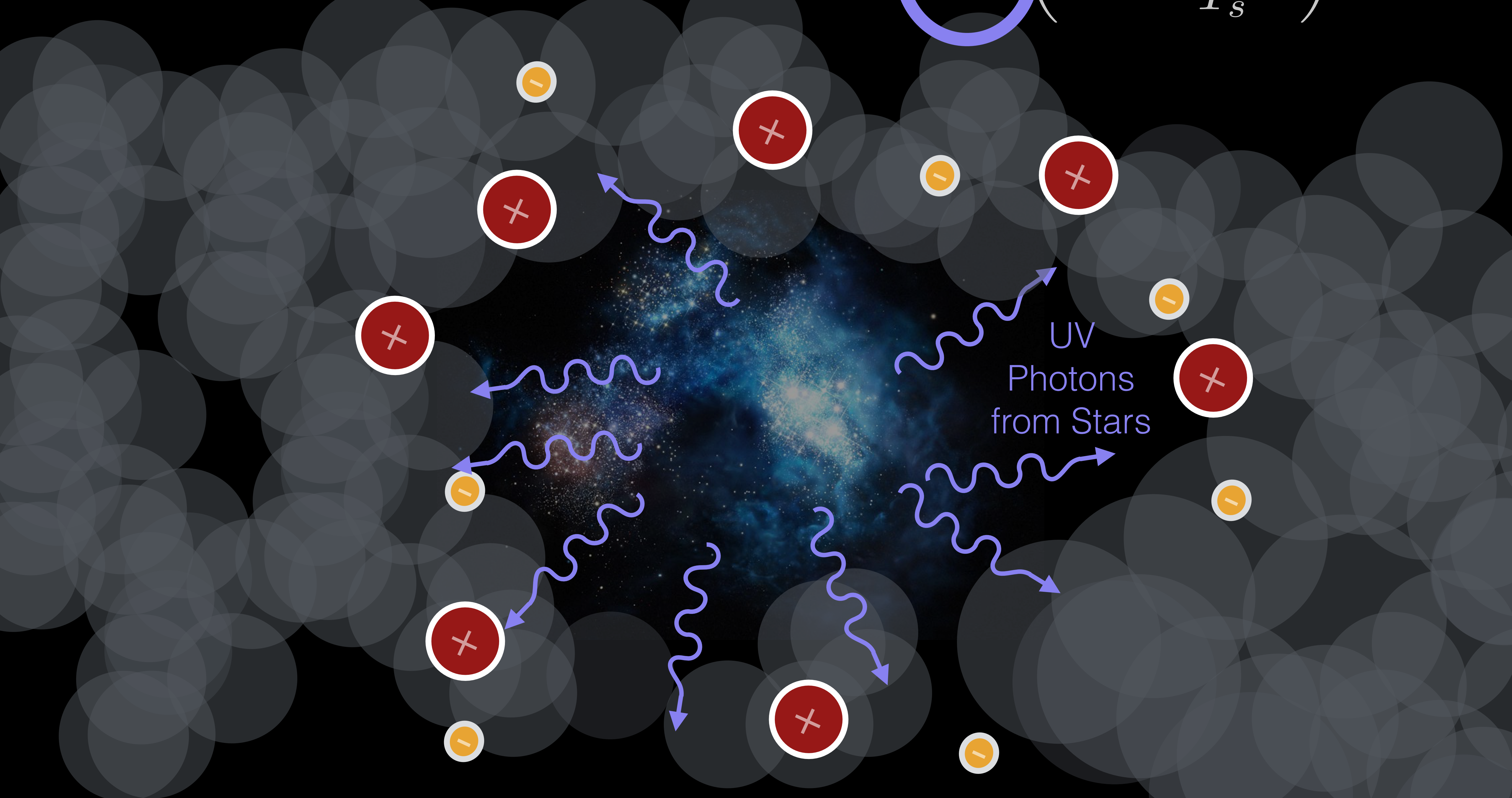
$$\delta T_b \propto x_{HI} \left(1 - \frac{T_{CMB}}{T_s}\right)$$

- **x_{HI}**: The Neutral Fraction -> ionizations?
- **T_s**: Spin Temperature -> Coupled to kinetic temperature of gas

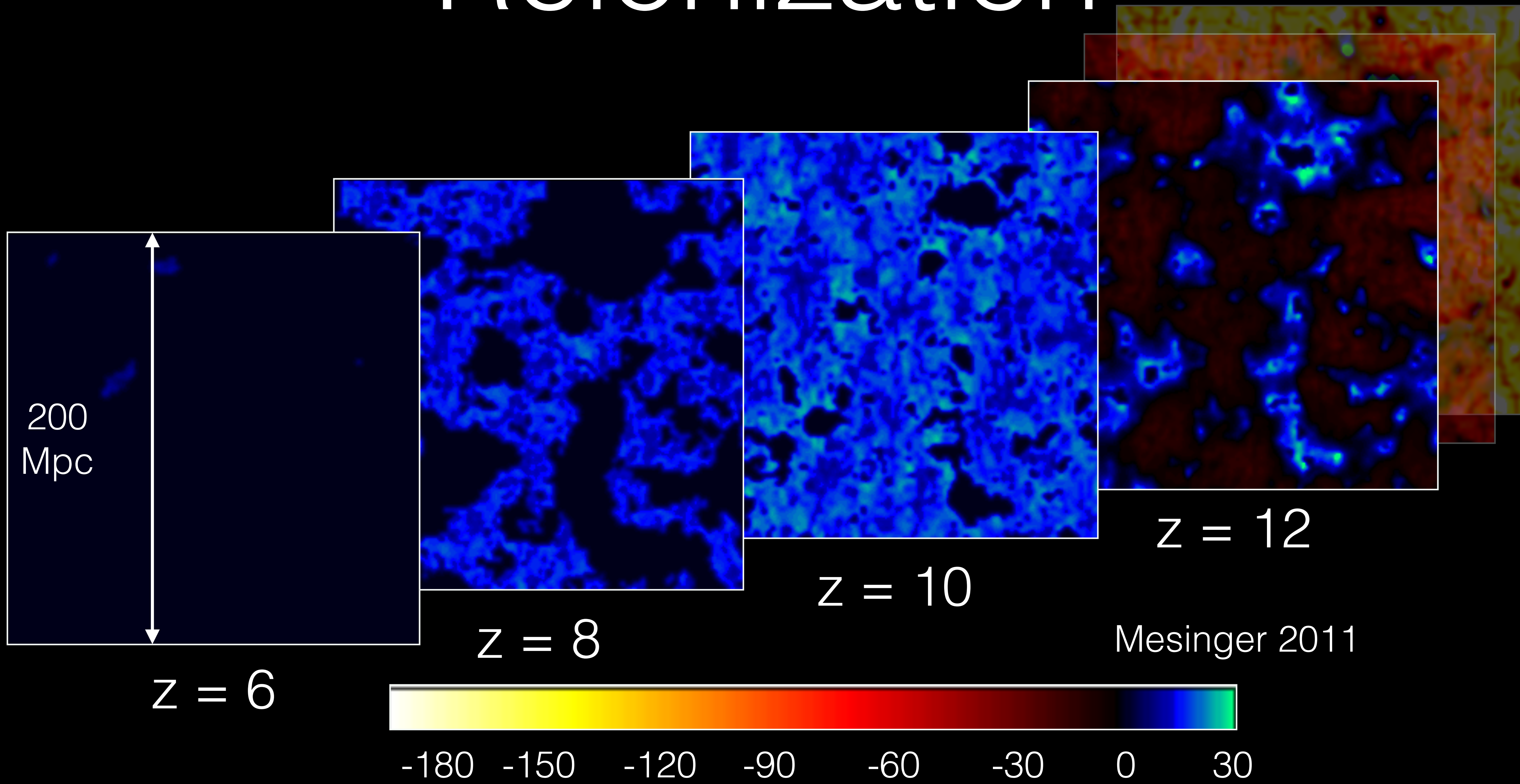
UV Photons from the first Stars

δT_b =Differential Brightness Temperature
= Radiation Temperature Difference from CMB

$$\delta T_b \propto x_{HI}\left(1 - \frac{T_{CMB}}{T_s}\right)$$



Reionization

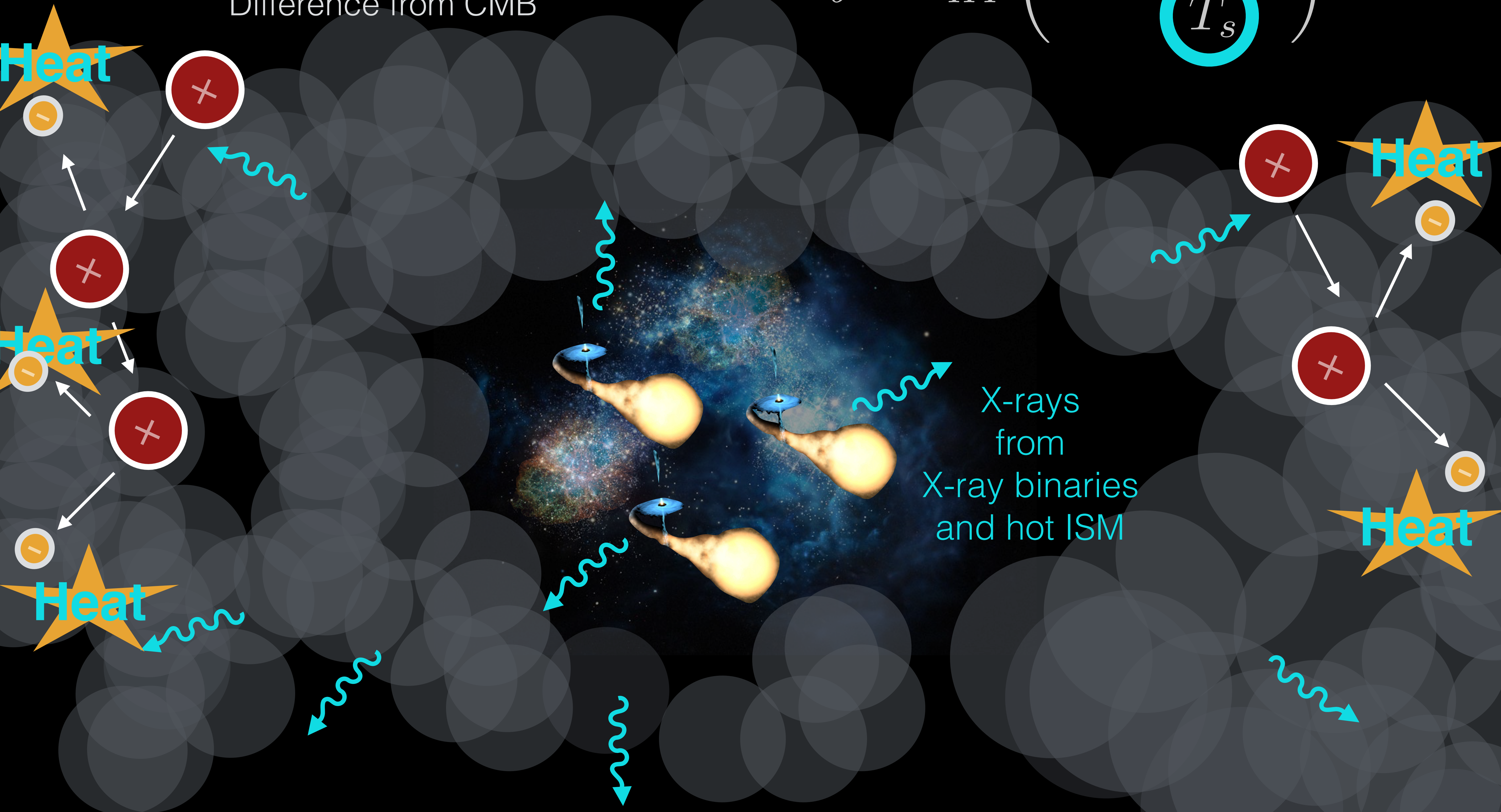


$$\delta T_b \propto x_H \left(1 - \frac{T_{CMB}}{T_s}\right) \quad \text{(mK)}$$

T_s: X-ray Heating

δT_b =Differential Brightness Temperature
= Radiation Temperature Difference from CMB

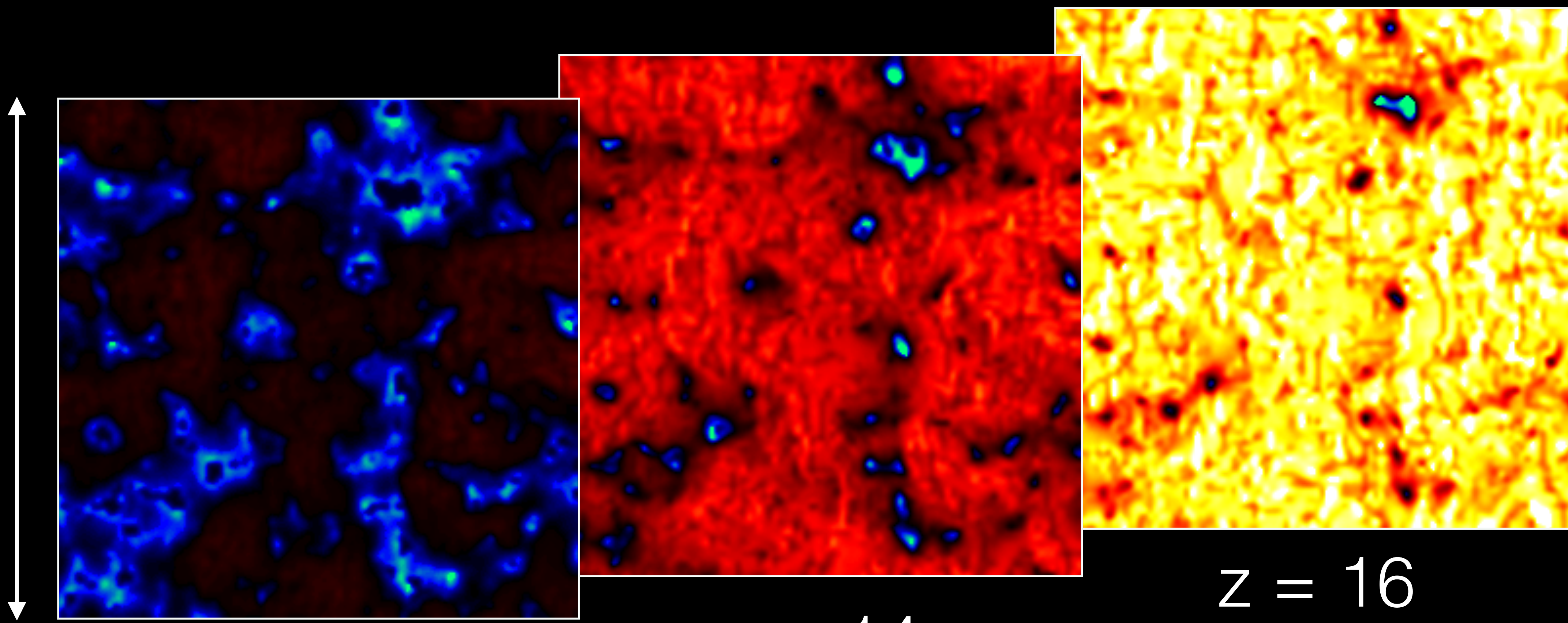
$$\delta T_b \propto x_{HI}\left(1 - \frac{T_{CMB}}{T_s}\right)$$



Heating

Blue = Emission against CMB
Yellow/Red=Absorption against CMB
Black=Same brightness as CMB with Ts=Tcmb or xHI=0

200 Mpc

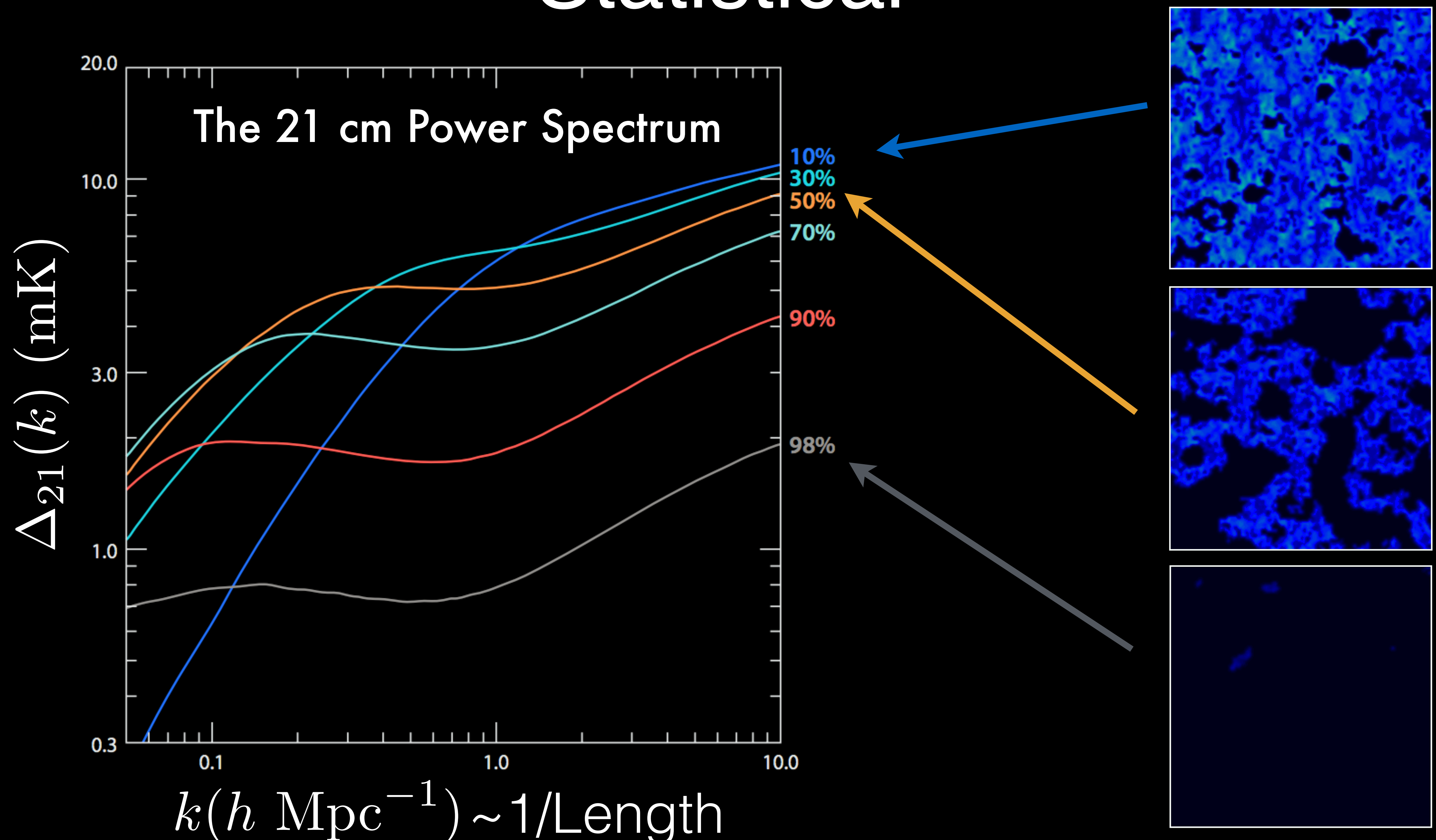


z = 12 z = 14 z = 16

-180 -150 -120 -90 -60 -30 0 30

$$\delta T_b \propto x_{HI}\left(1 - \frac{T_{CMB}}{T_s}\right)$$ (mK)

Early Detections of 21cm will be Statistical



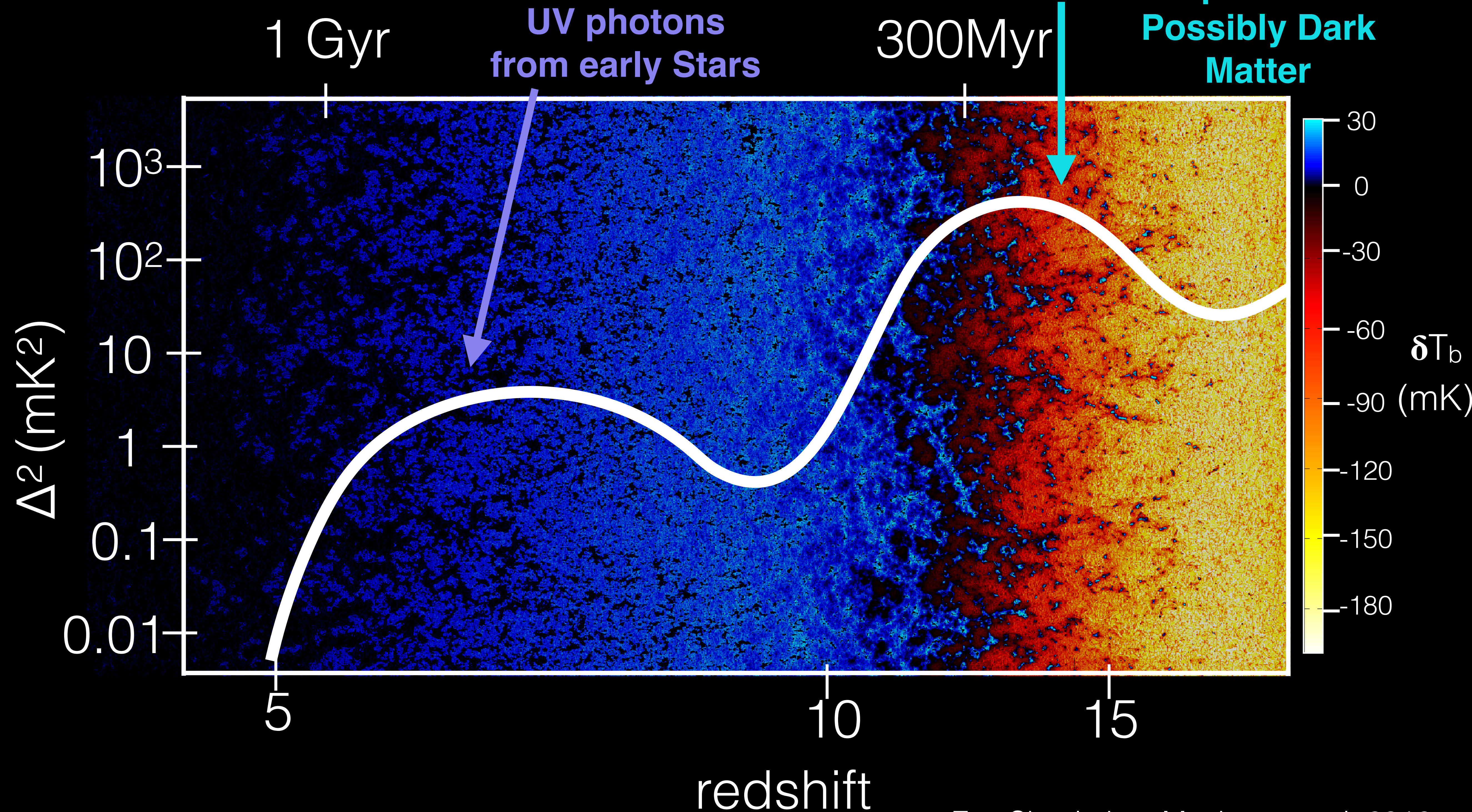
Slide adopted from Josh Dillon

Barkana (2009), Morales & Wyithe (2010)

$$\delta T_b \propto x_{HI}\left(1 - \frac{T_{CMB}}{T_s}\right)$$

Reionization
UV photons
from early Stars

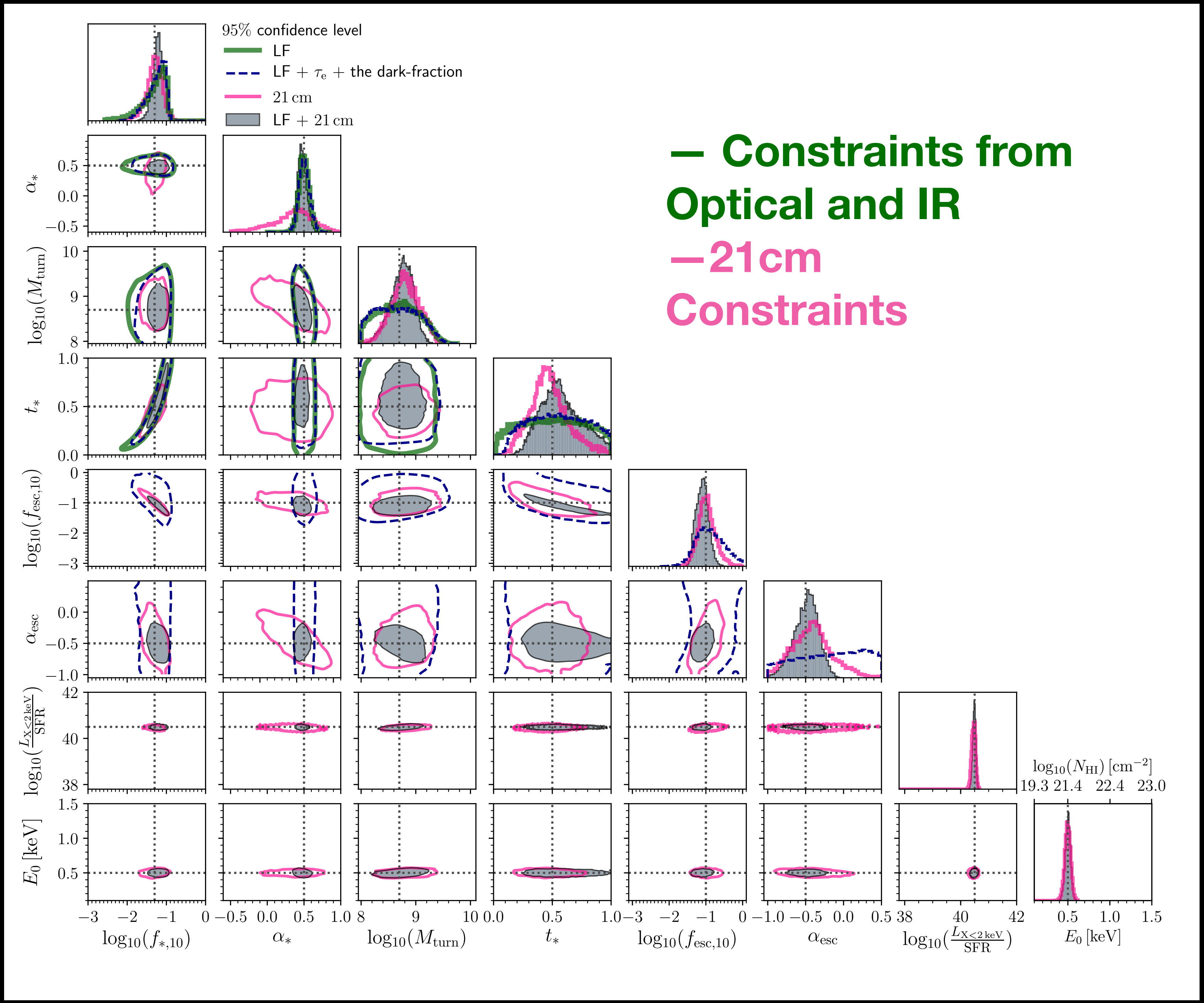
Heating
X-rays
from first Stellar
Black Holes
Supernovae
Possibly Dark
Matter



width=1600Mpc

Eos Simulation: Mesinger et al. 2016

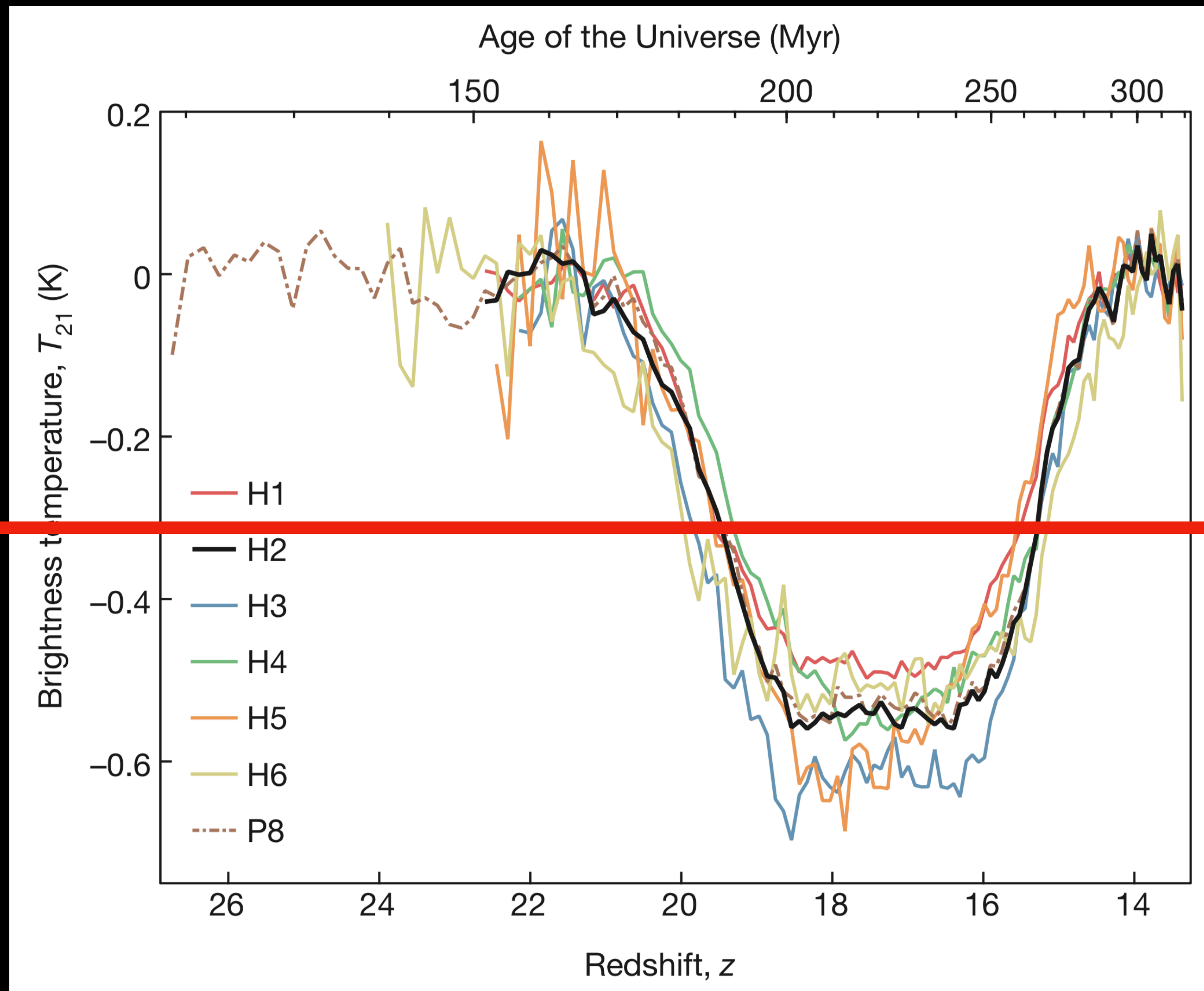
What we hope to ultimately obtain are statistical constraints on the Properties of the early Sources



— Constraints from Optical and IR

—21cm Constraints

Park+2018

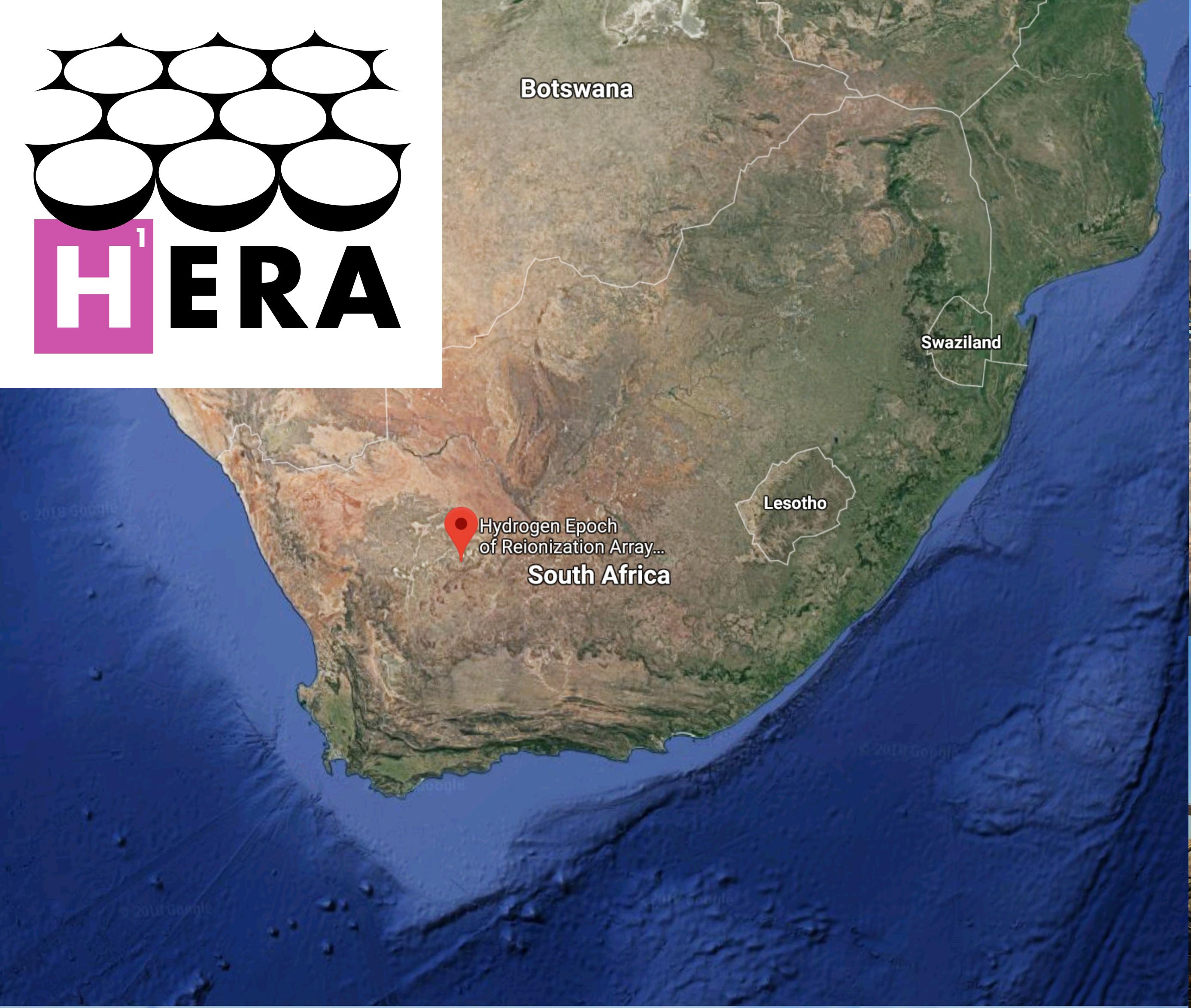


Adiabatic Cooing Limit

All Bets are off if EDGEs is confirmed

See Raul's Talk

HERA

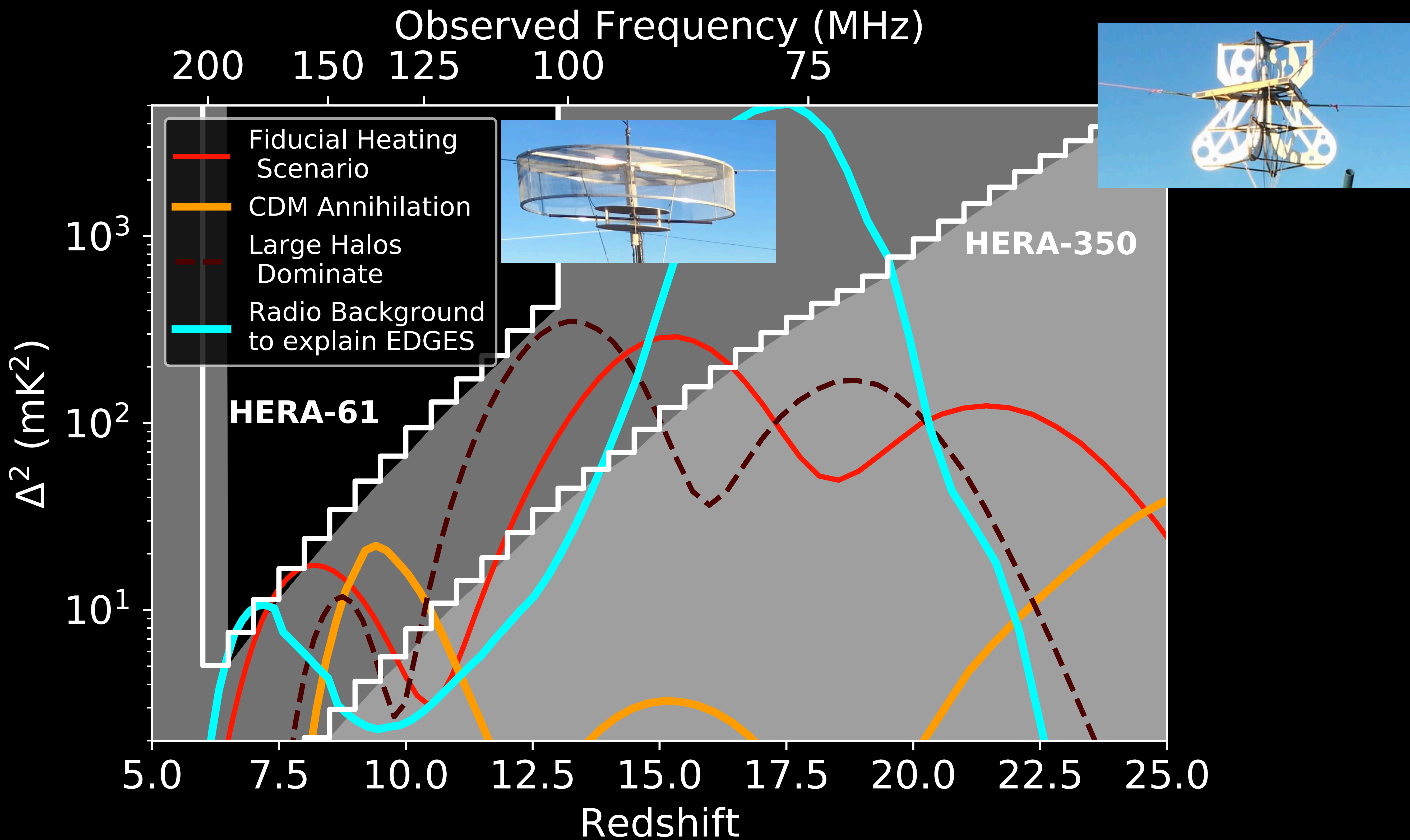

Botswana
Swaziland
Lesotho
Hydrogen Epoch
of Reionization Array...
South Africa


2017-2018 initial deployment of 61,
100-200 MHz PAPER RF chains.


Currently being replaced with 350,
50-250 MHz RF chains


139 Dishes (~61 signal chains)
Currently deployed at SKA-MID Site


Funded to build and analyze
350 dishes/signal chains.


Observed Frequency (MHz)
200
150
125
100
75
Fiducial Heating Scenario
CDM Annihilation
Large Halos Dominate
Radio Background to explain EDGES
HERA-61
HERA-350
10^3
10^2
10^1
Δ^2 (mK^2)
5.0
7.5
10.0
12.5
15.0
17.5
20.0
22.5
25.0
Redshift

HERA Timeline
A Staged Deployment

- **Past Year:** Deployed 61 first generation feeds with PAPER backend. Analysis is ongoing. 139 dishes constructed.

- **Currently:** Deploying 50 second generation feeds with <u>new signal chain.</u>

- **FY 2019/2020:** Observe 80-200 feeds: Validate new system performance

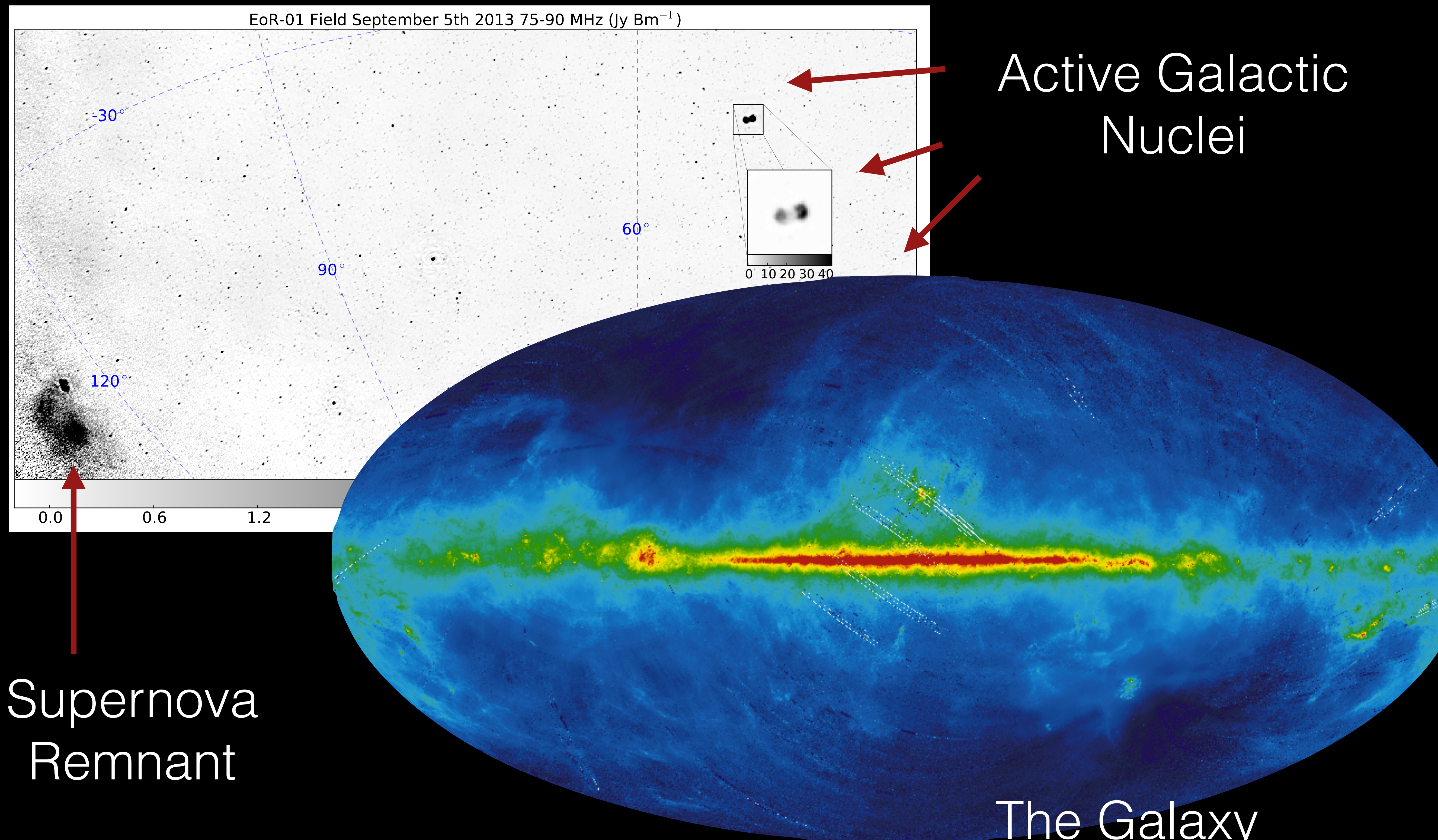
  - Tweak design based on 50-80 feed results.

- **FY 2020-2023:** Observe with 200-350 feeds. Precision constraints on the Cosmic Dawn.

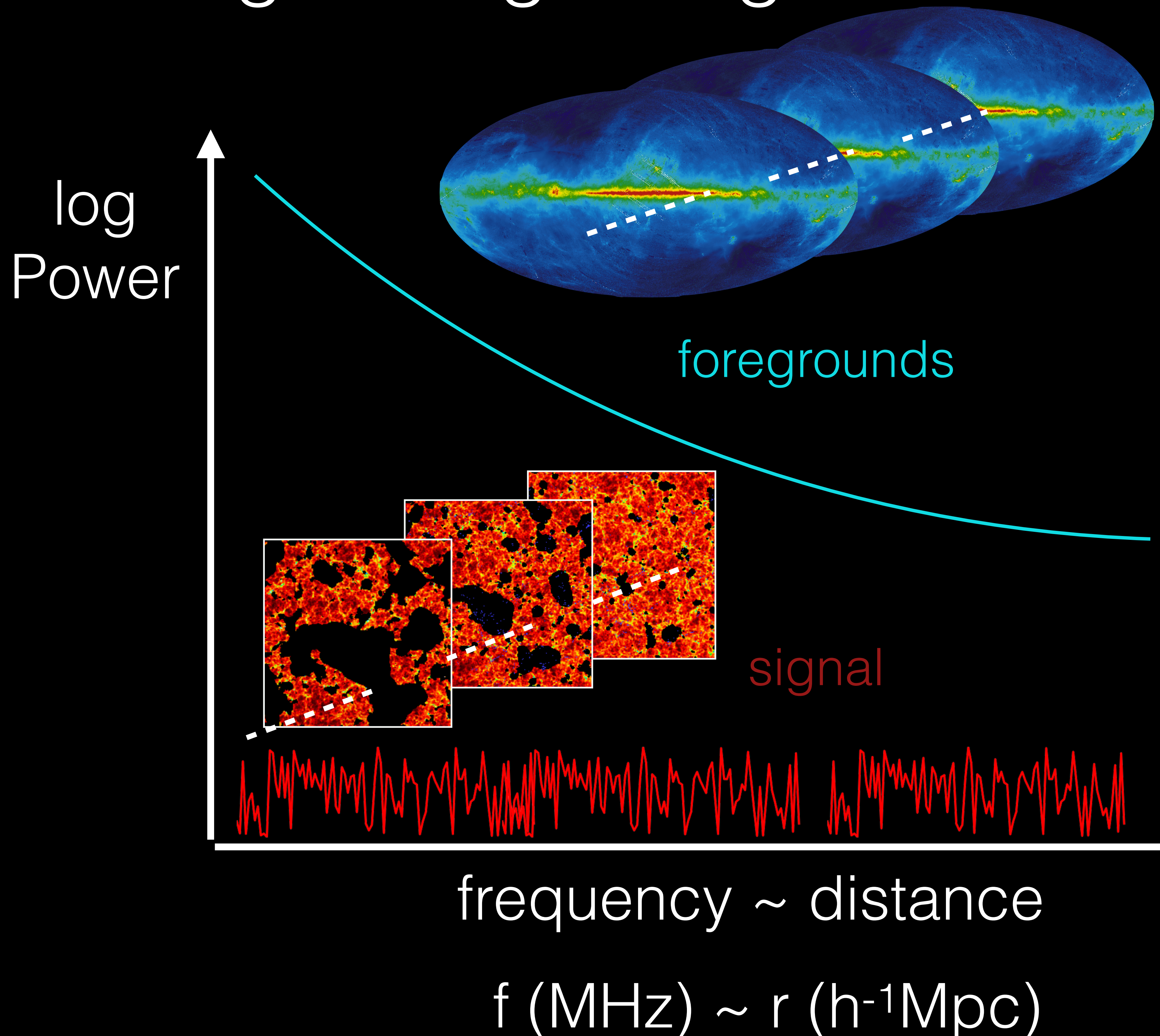
Systematics

And how we are dealing with them.

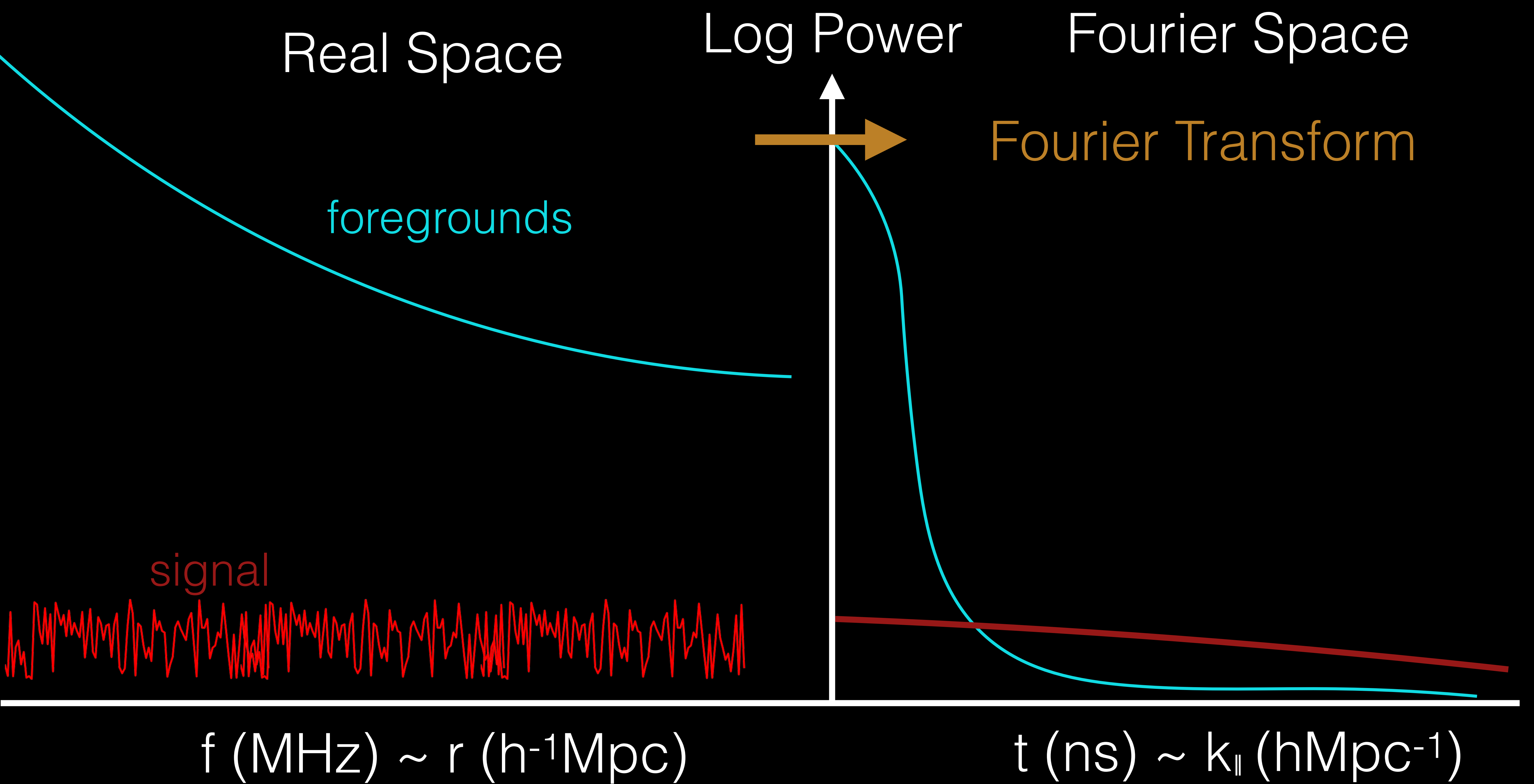
Radio Foregrounds: ~**10⁴x** the signal level!

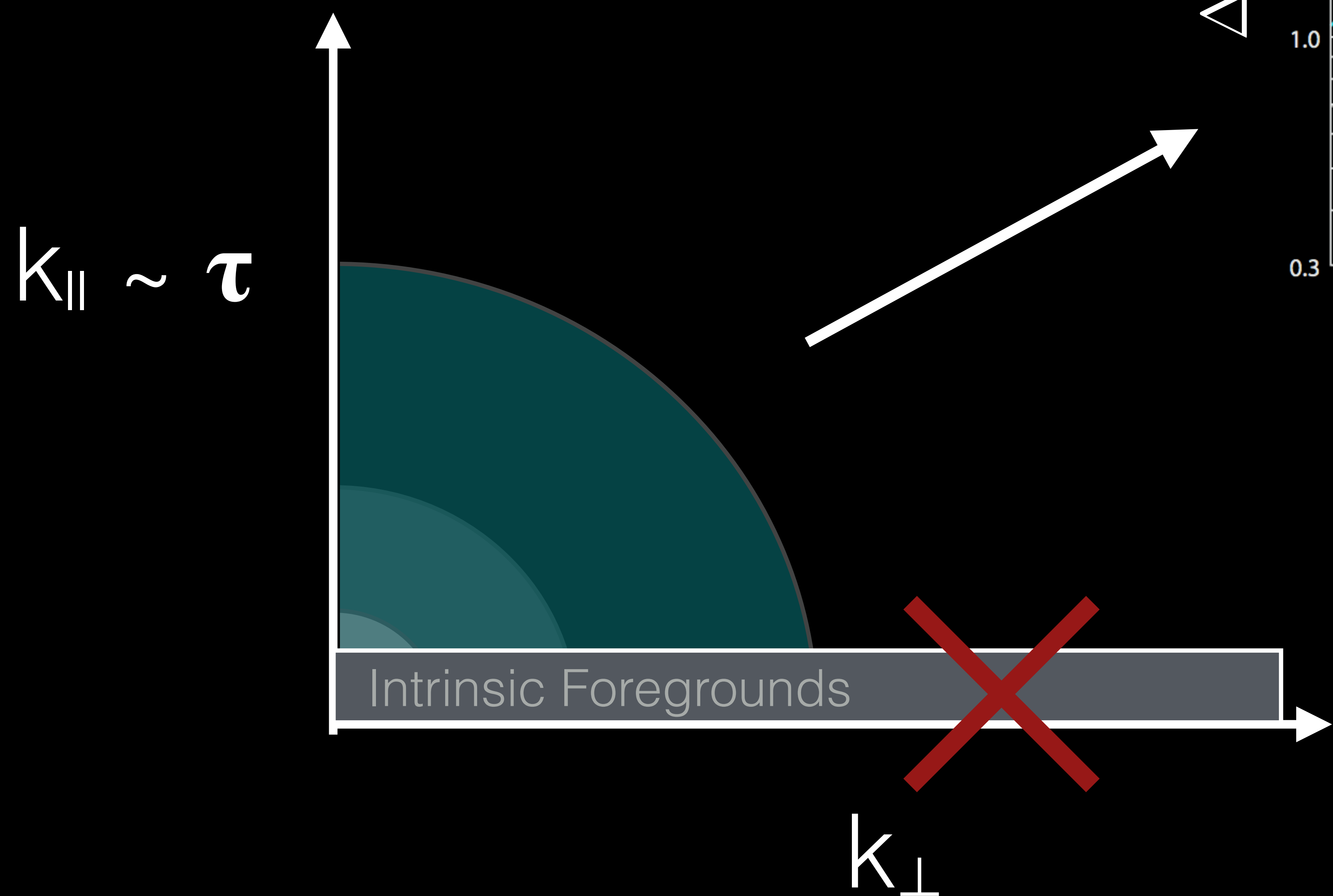


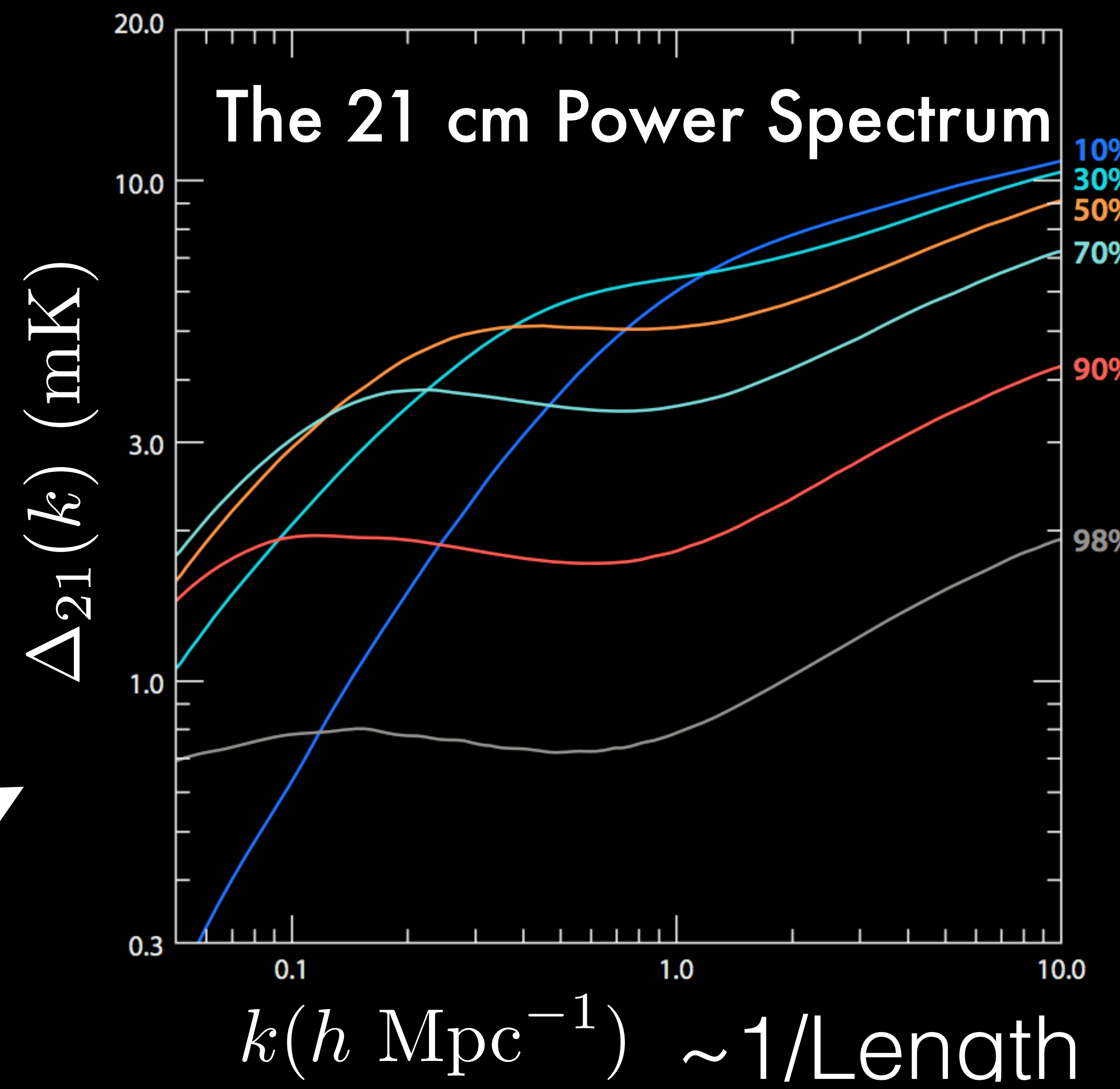
Distinguishing Foregrounds from Signal



Isolating Foregrounds Using the Fourier Transform

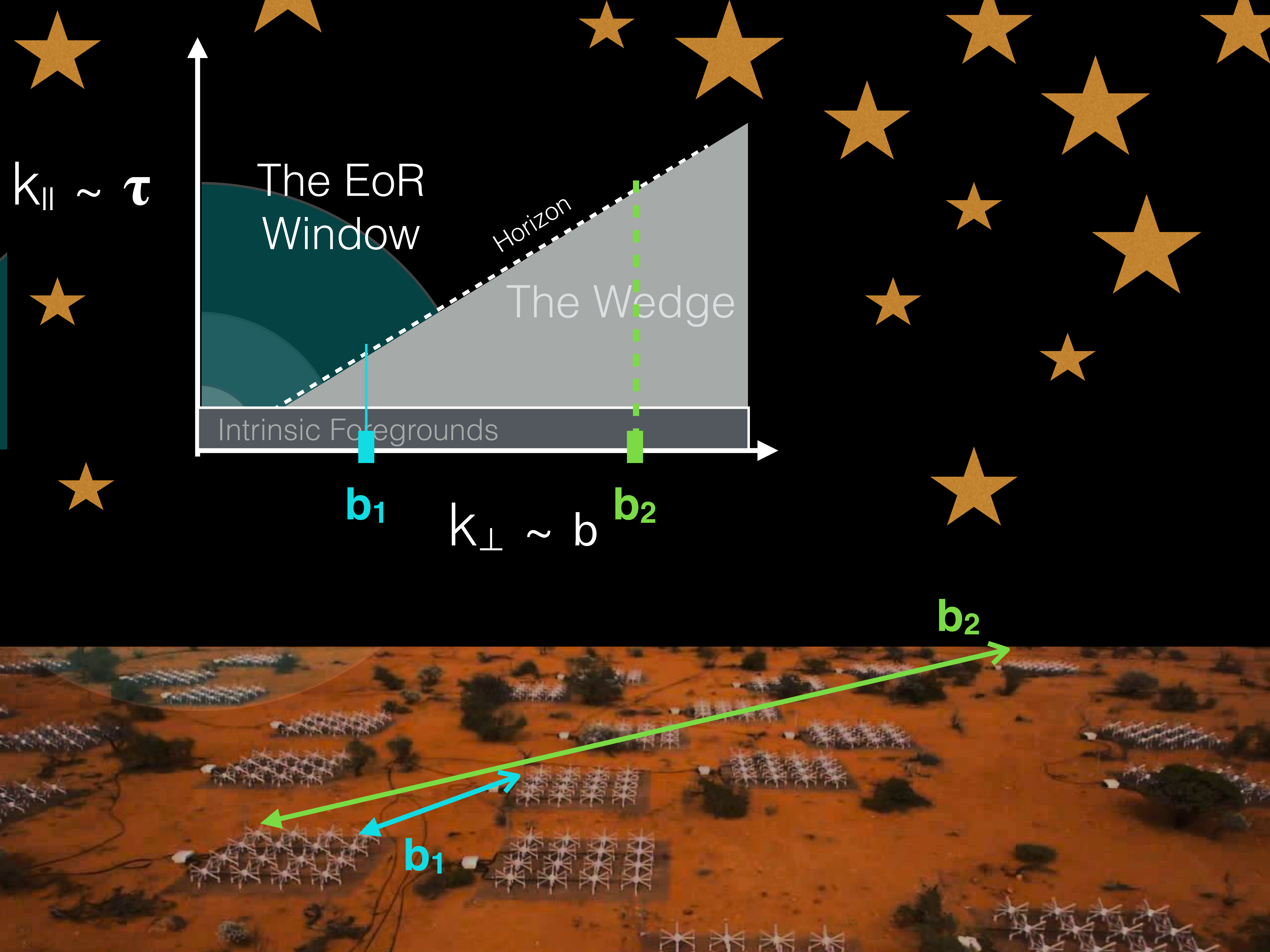




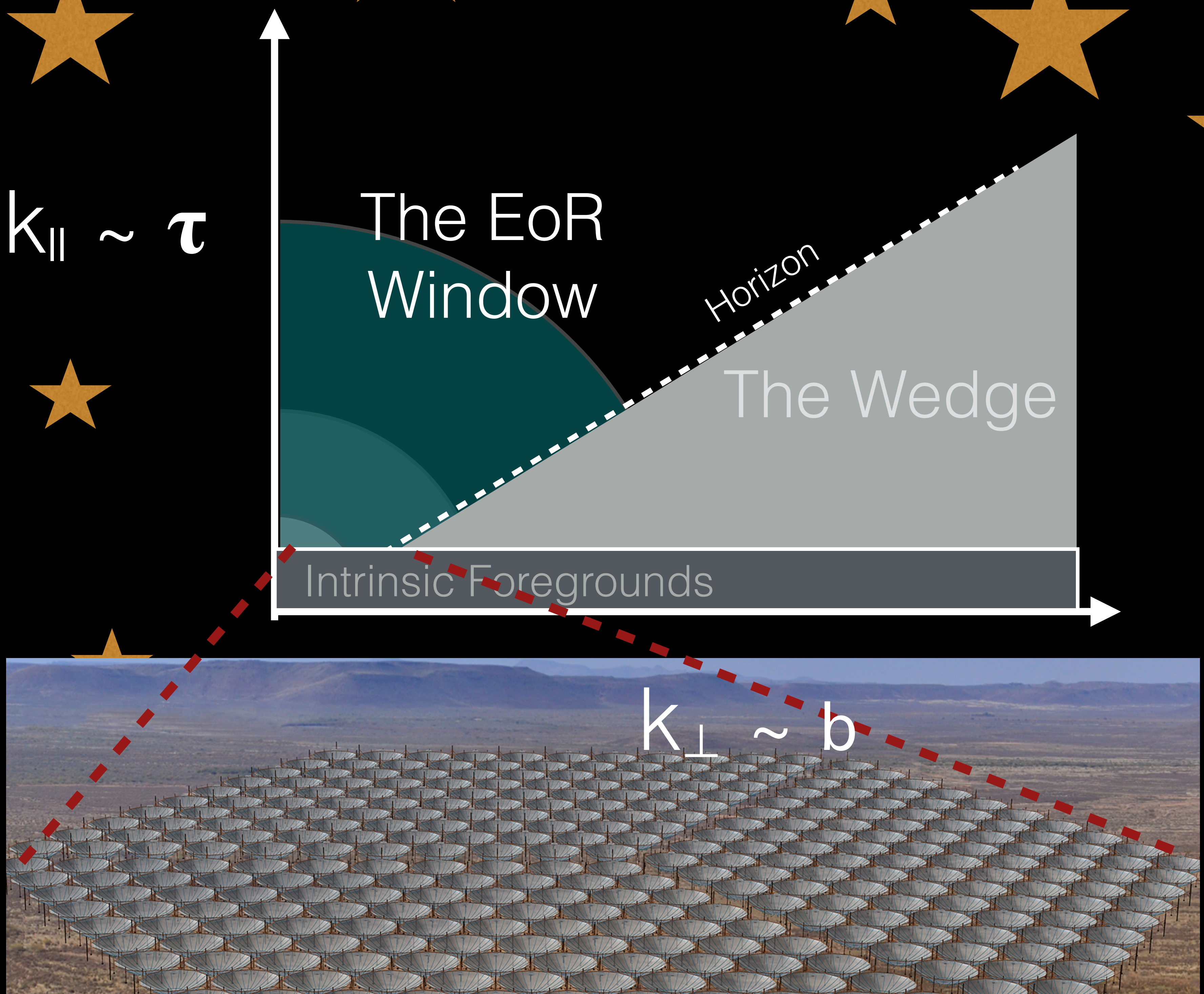


$k^2 = k_\parallel^2 + k_\perp^2$

Intrinsic Foregrounds


$k_{\parallel} \sim \tau$
The EoR Window
Horizon
The Wedge
Intrinsic Foregrounds
b_1
$k_{\perp} \sim b$
b_2
b_2
b_1

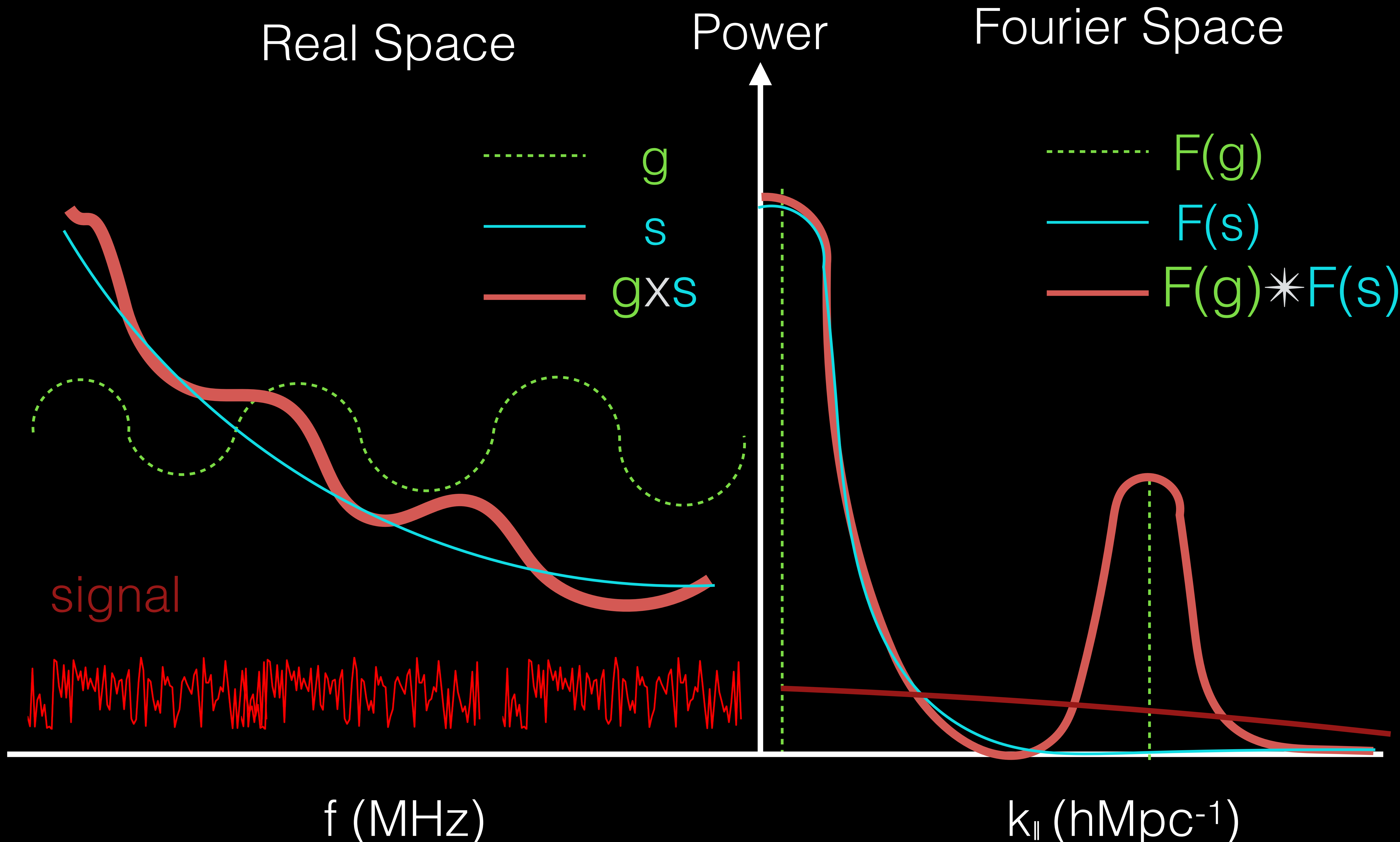
HERA's Strategy: **Avoid** Foregrounds



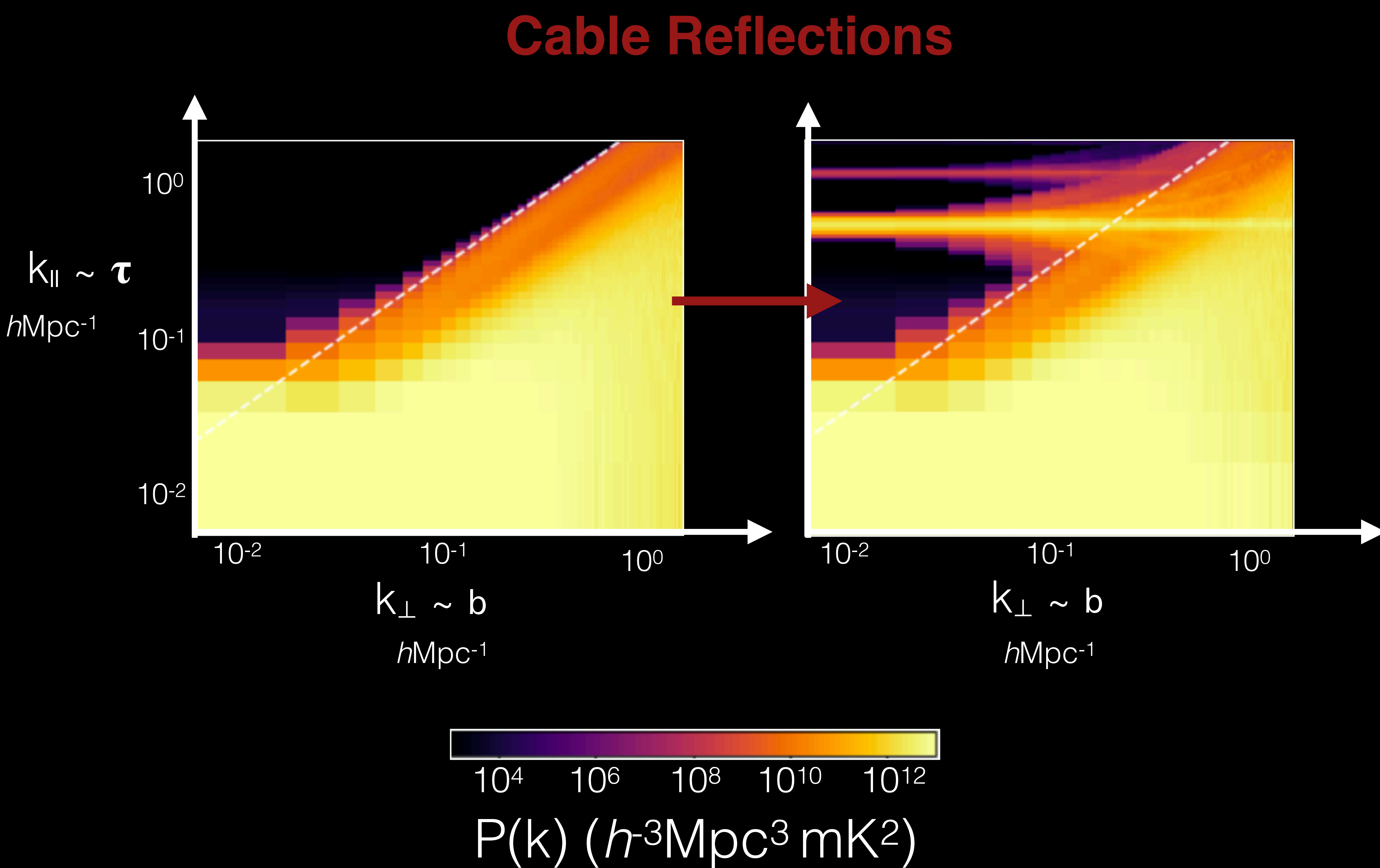
Outriggers give HERA Modest imaging capabilities Dillon+2017

If we have **Instrumental Spectral Structure**

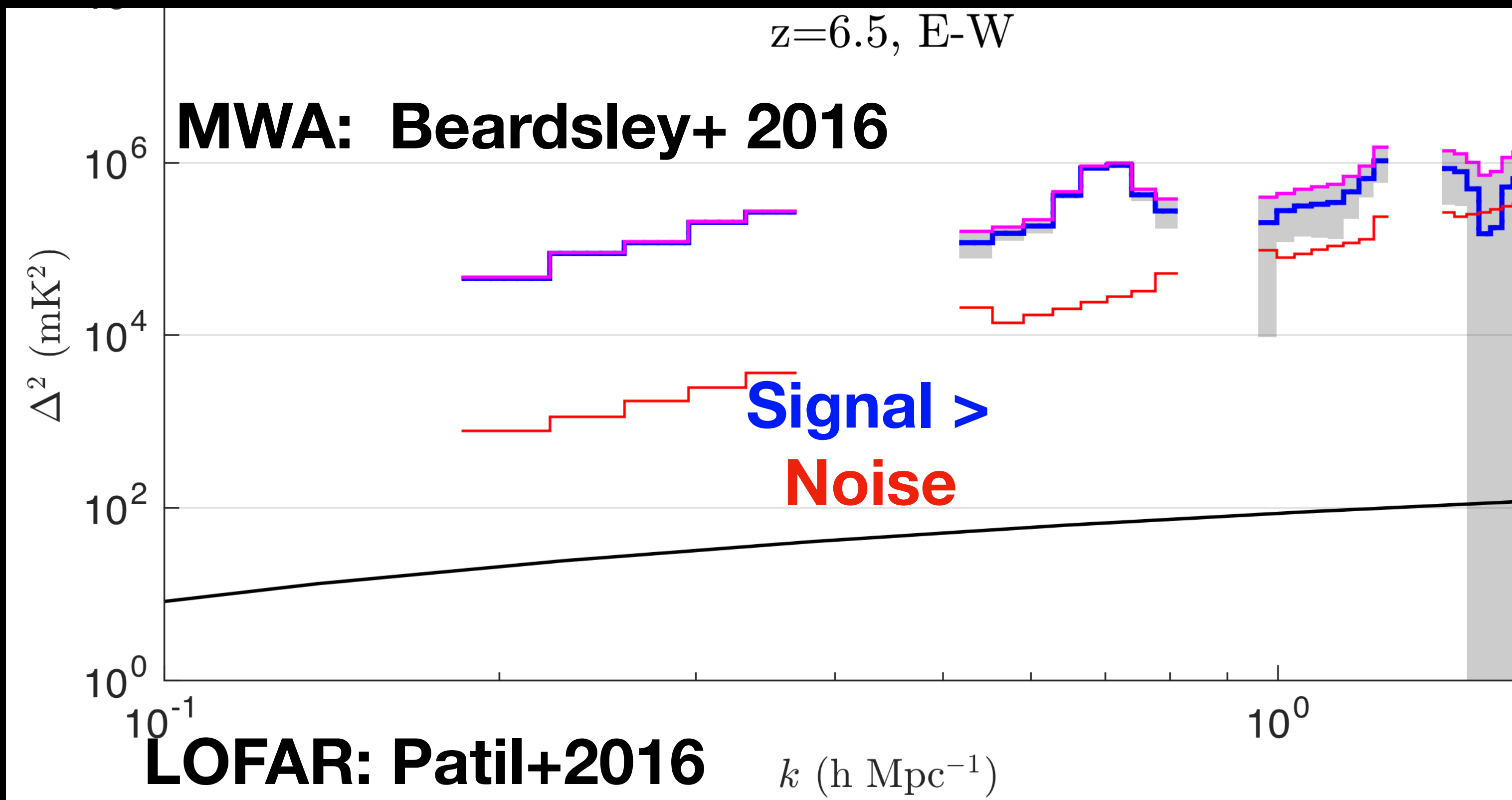
Avoidance Fails!

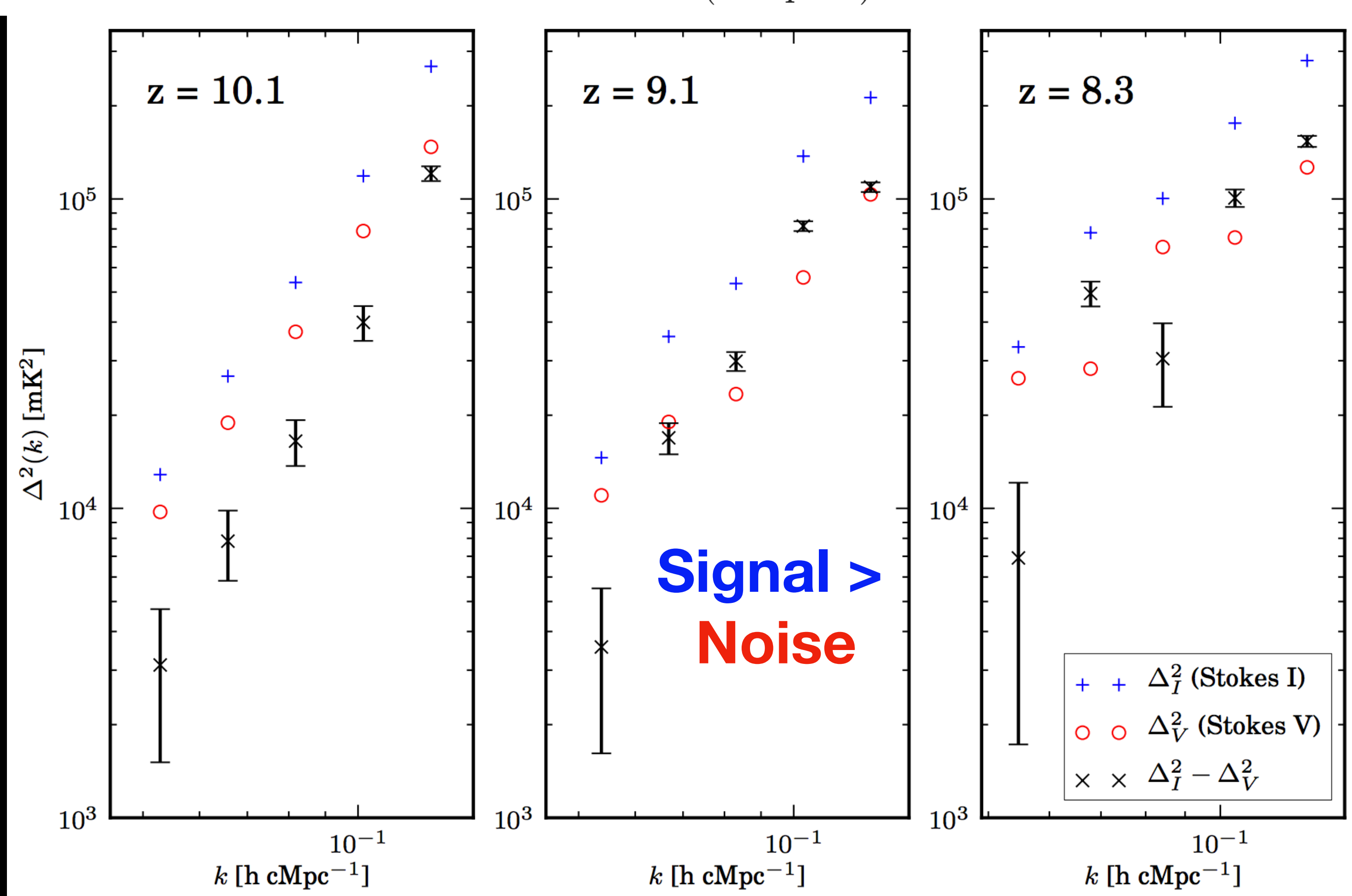


The Effect of uncalibrated Cable Reflections

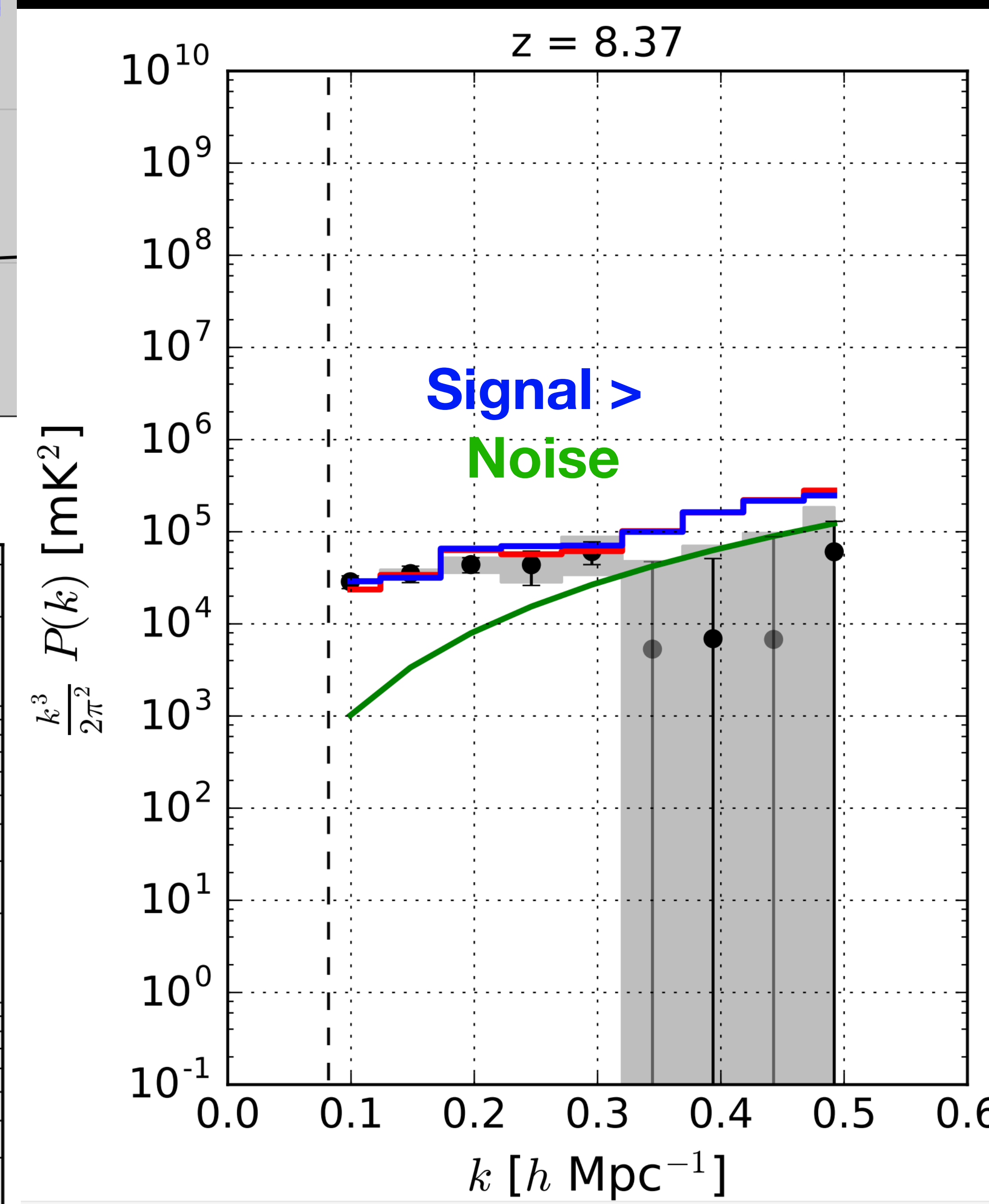


Existing Limits are set by Systematics





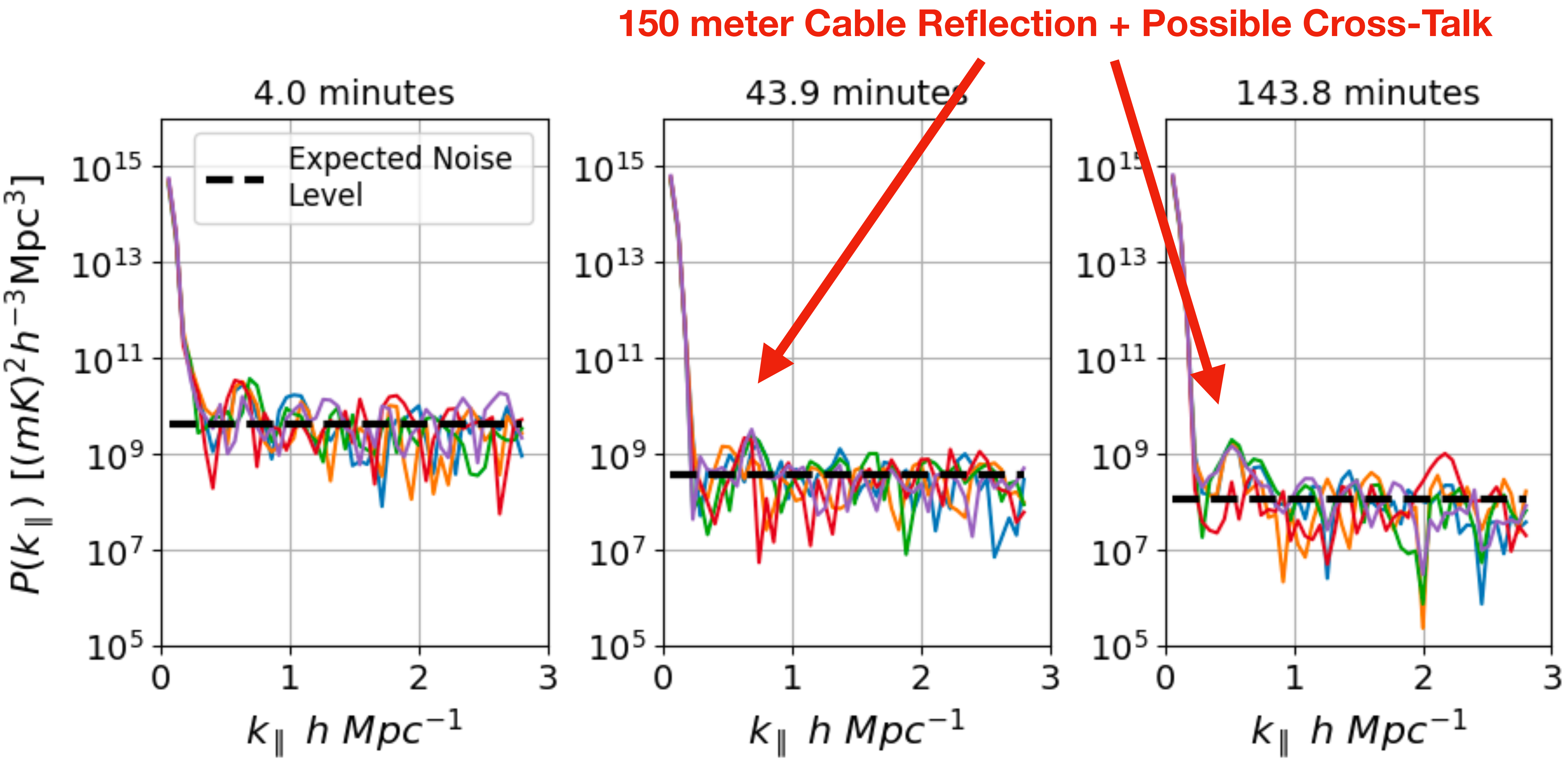
PAPER: Cheng+2018



See Talks by
Nichole, Carina, and Matt

HERA-47: PAPER feed and analog chain.

Similar Structures appear in initial HERA deployment



Kern + In Prep

Spectrally Smooth*

^

"All you need is paperclips and a supercomputer"

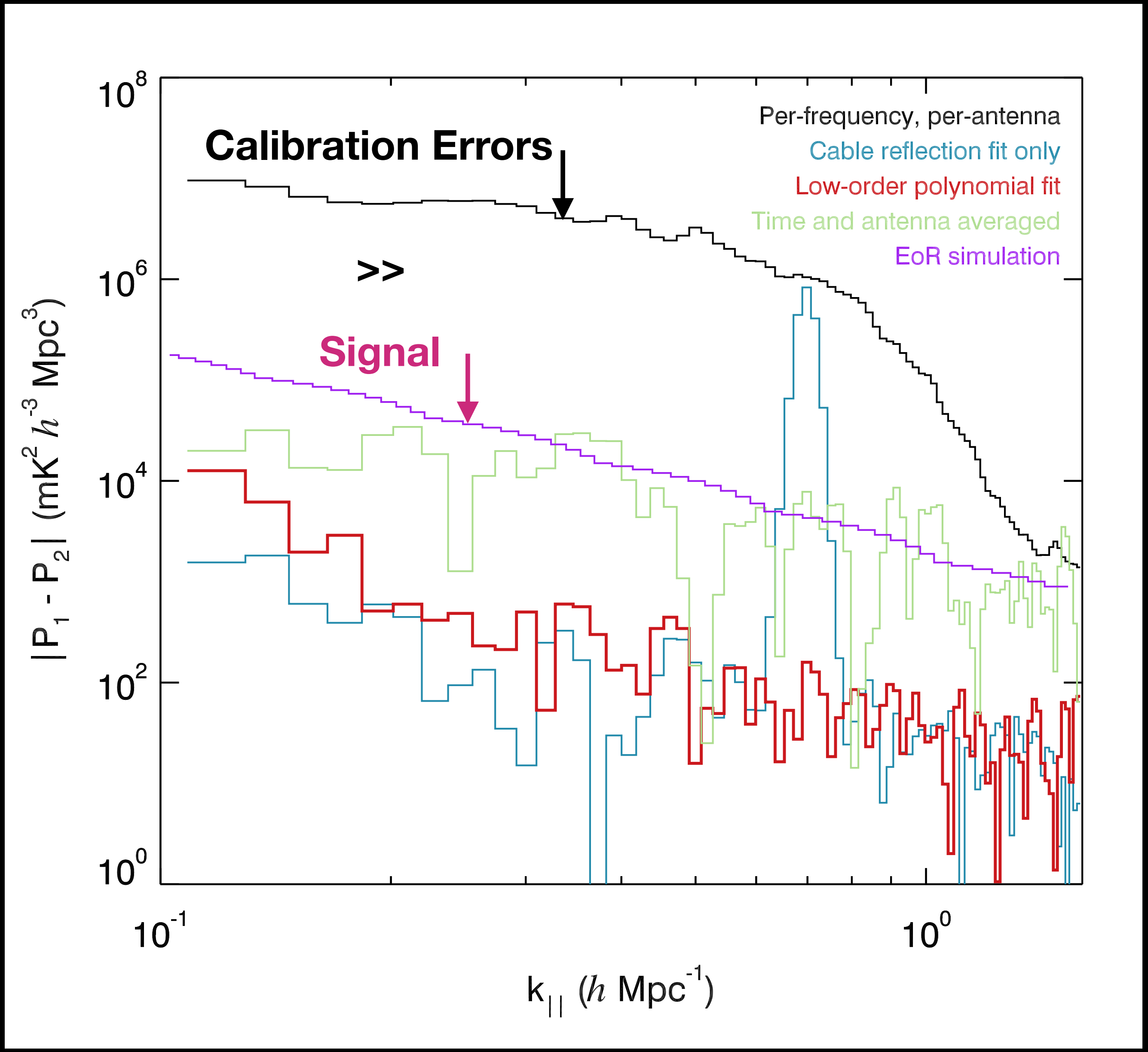
-Don Backer

***up to one part in ~10^{-5}**

Calibration <u>should</u> remove spectral structure

Sky-based calibration errors Exceed the power-spectrum level

MWA Simulation



Barry+ 2017

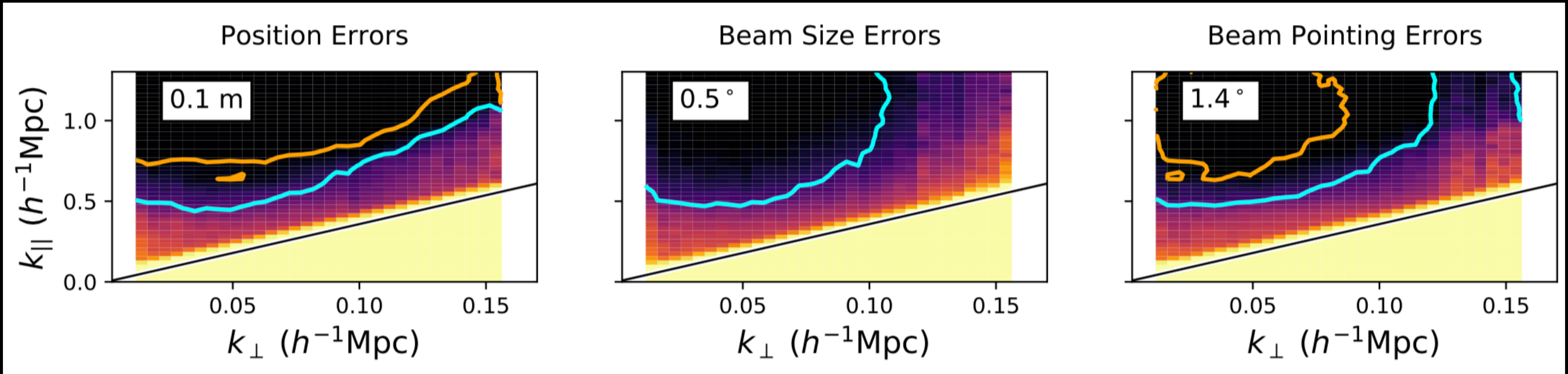
Will also limit nominal SKA-low designs.

also AEW+ 2017, Patil+ 2017, Trott+2017

See Ronniy Joseph's Talk Later Today

HERA's Redundant Calibration faces similar challenges as Sky-Based.

Non-redundancies introduce calibration errors that also fill in the "window".

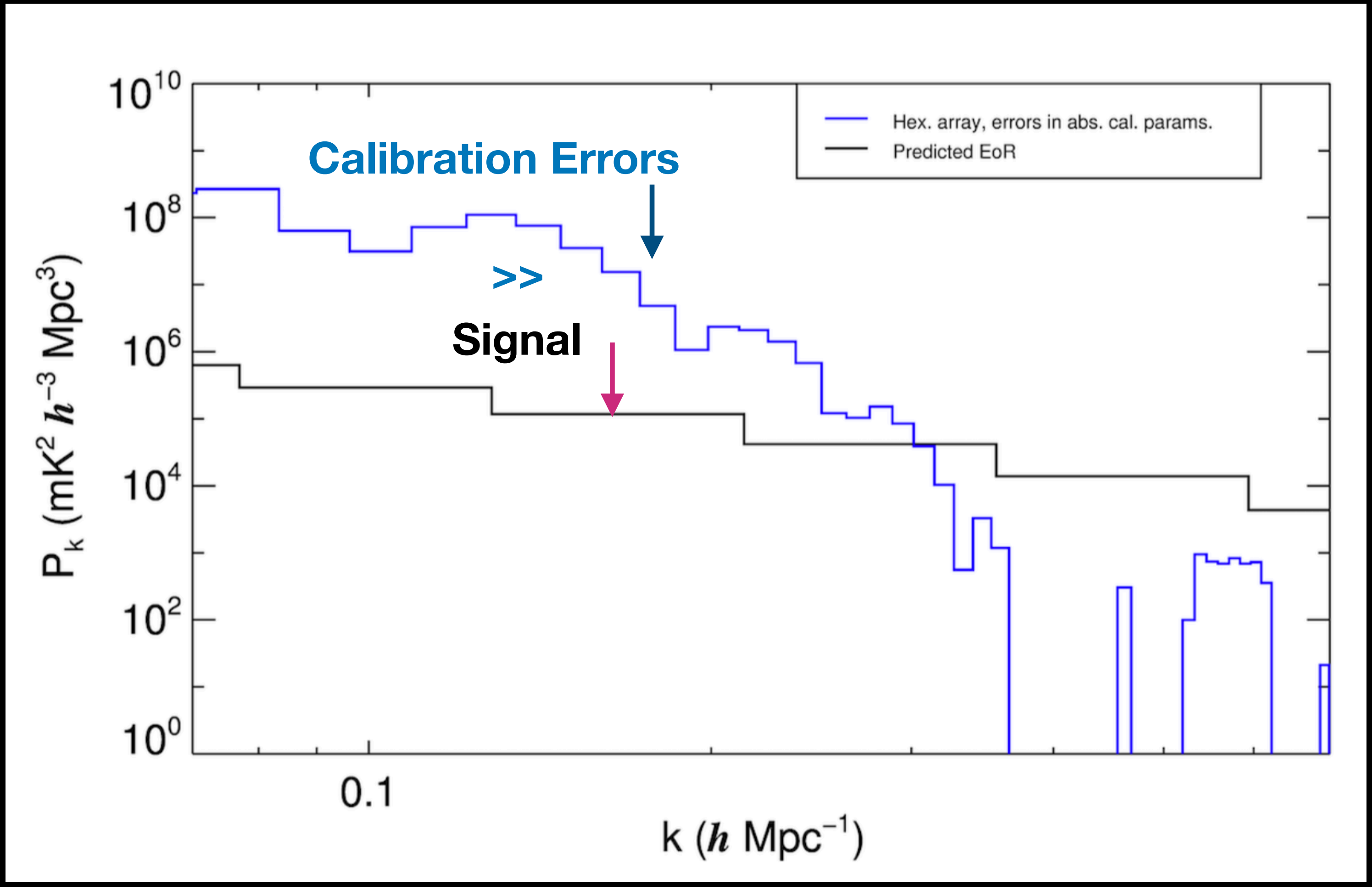


Orosz+2018

See Ronniy Joseph's Talk Later Today

HERA's Redundant Cal has its own limitations

An Imperfect sky-model leads to "abs-cal" errors



Byrne+2018

See Ronniy Joseph's Talk Later Today

Ways we are trying to deal with spectral structure

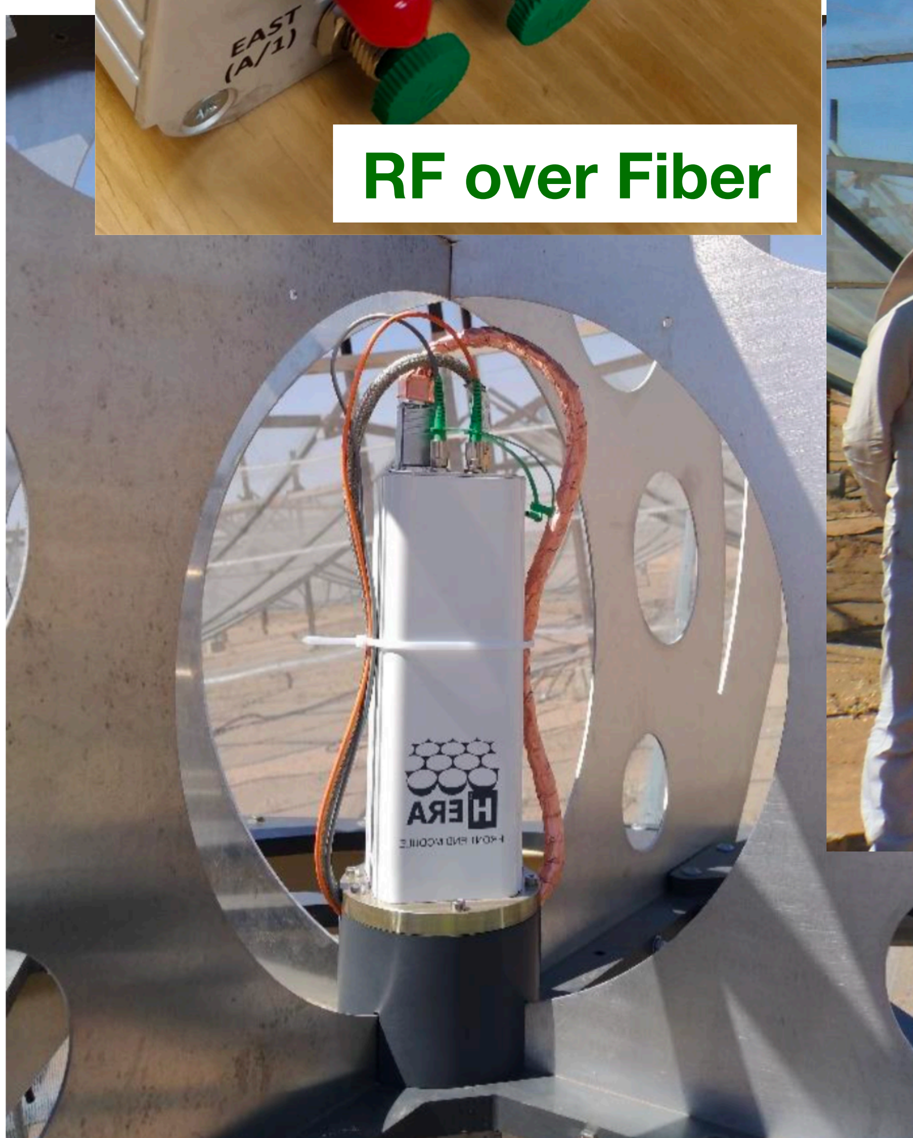
1. **Make sure our new signal path is "spectrally smooth".**

2. **Make sure that the array is sufficiently redundant to avoid calibration errors.**

3. **Figure out ways to robustify redundant calibration against non-redundancy and sky-model incompleteness.**

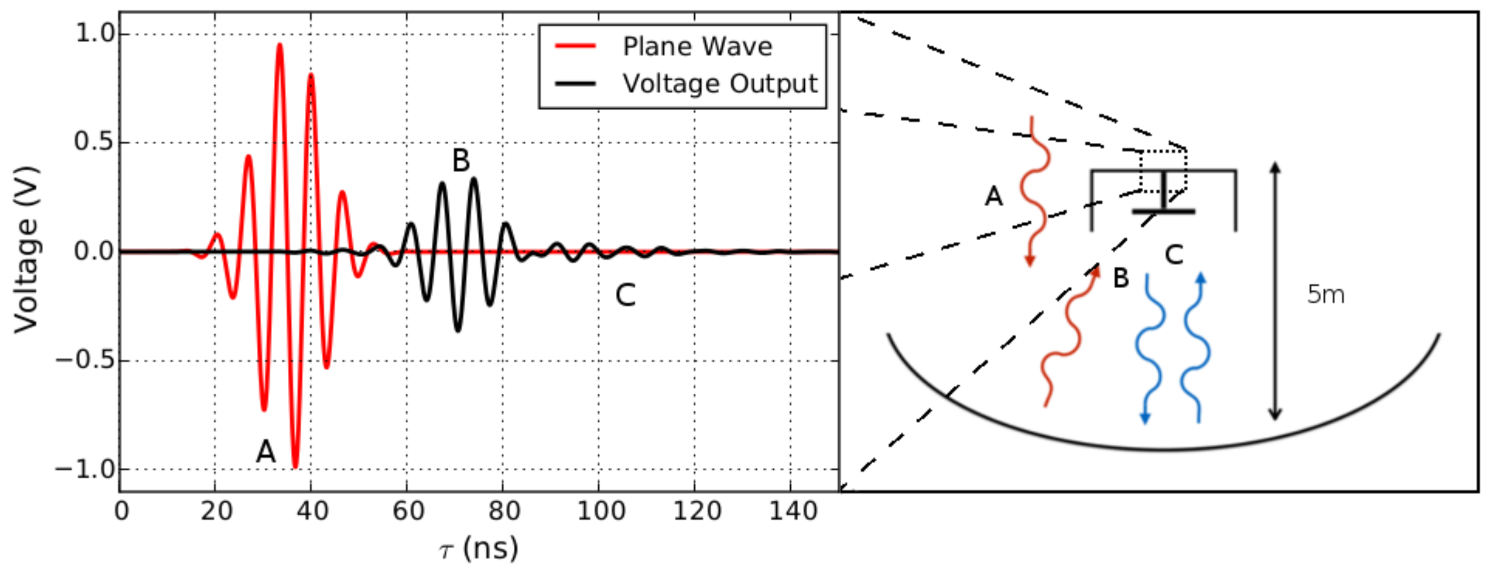
UNIVERSITY OF CAMBRIDGE

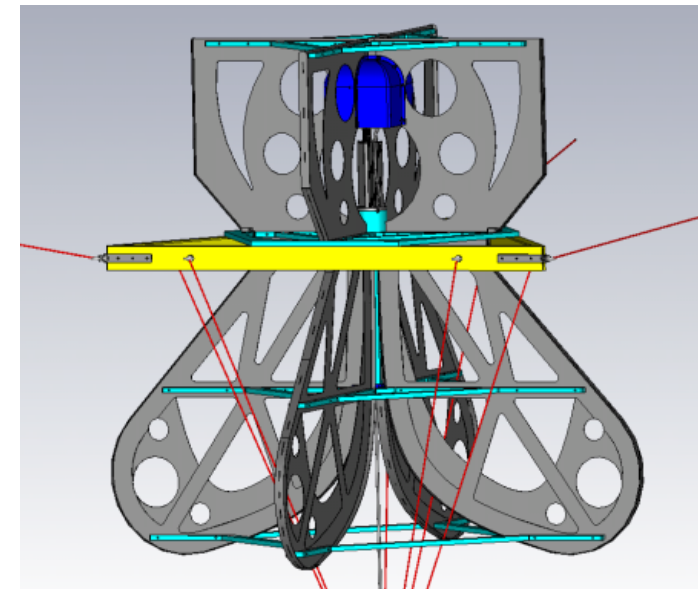
To mitigate reflections, the signal chain uses RF over Fiber.

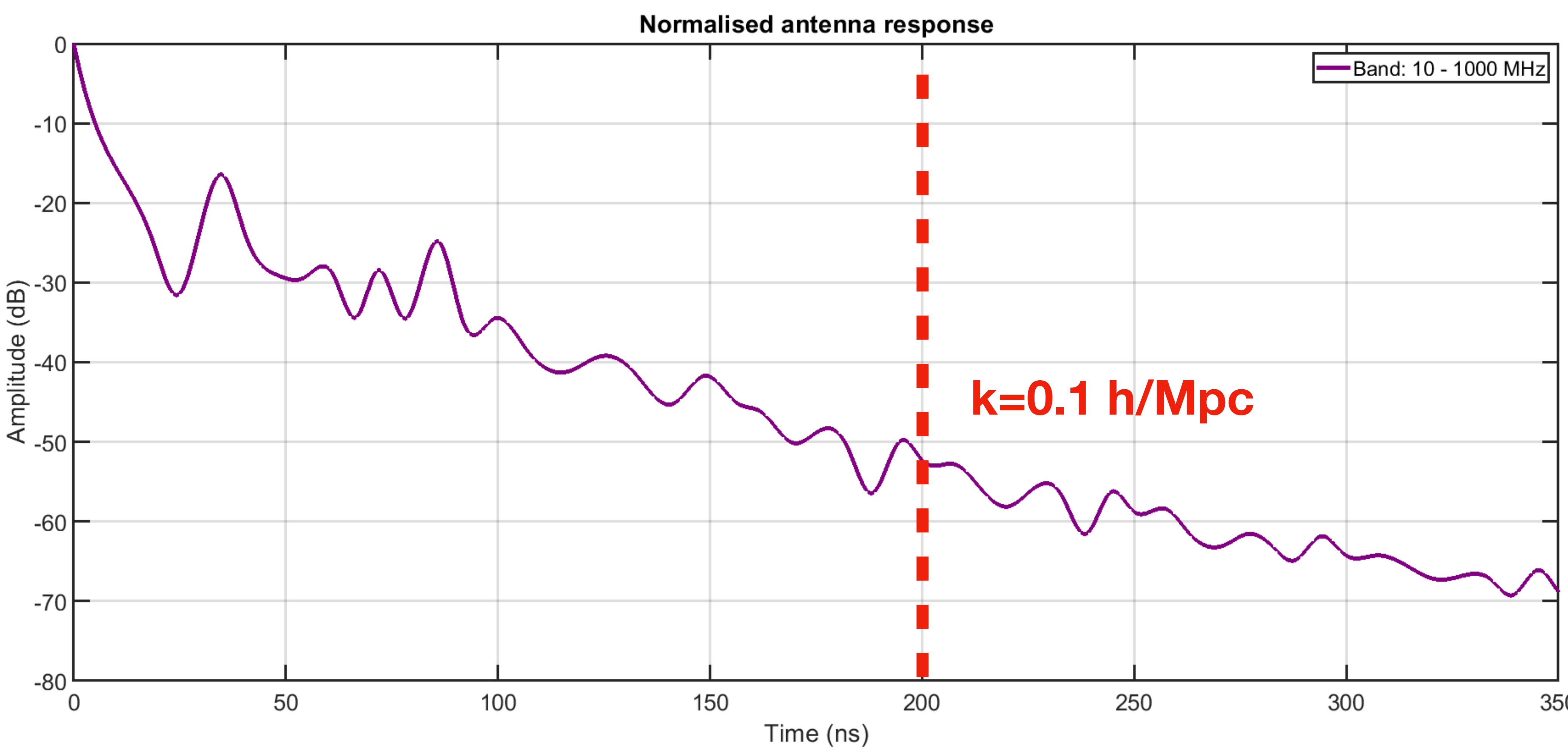


Site trip deploying first RFoF chains and new feeds

We use Electromagnetic Simulations to optimize feed and RF front-end together







Fagnoni+ in prep.

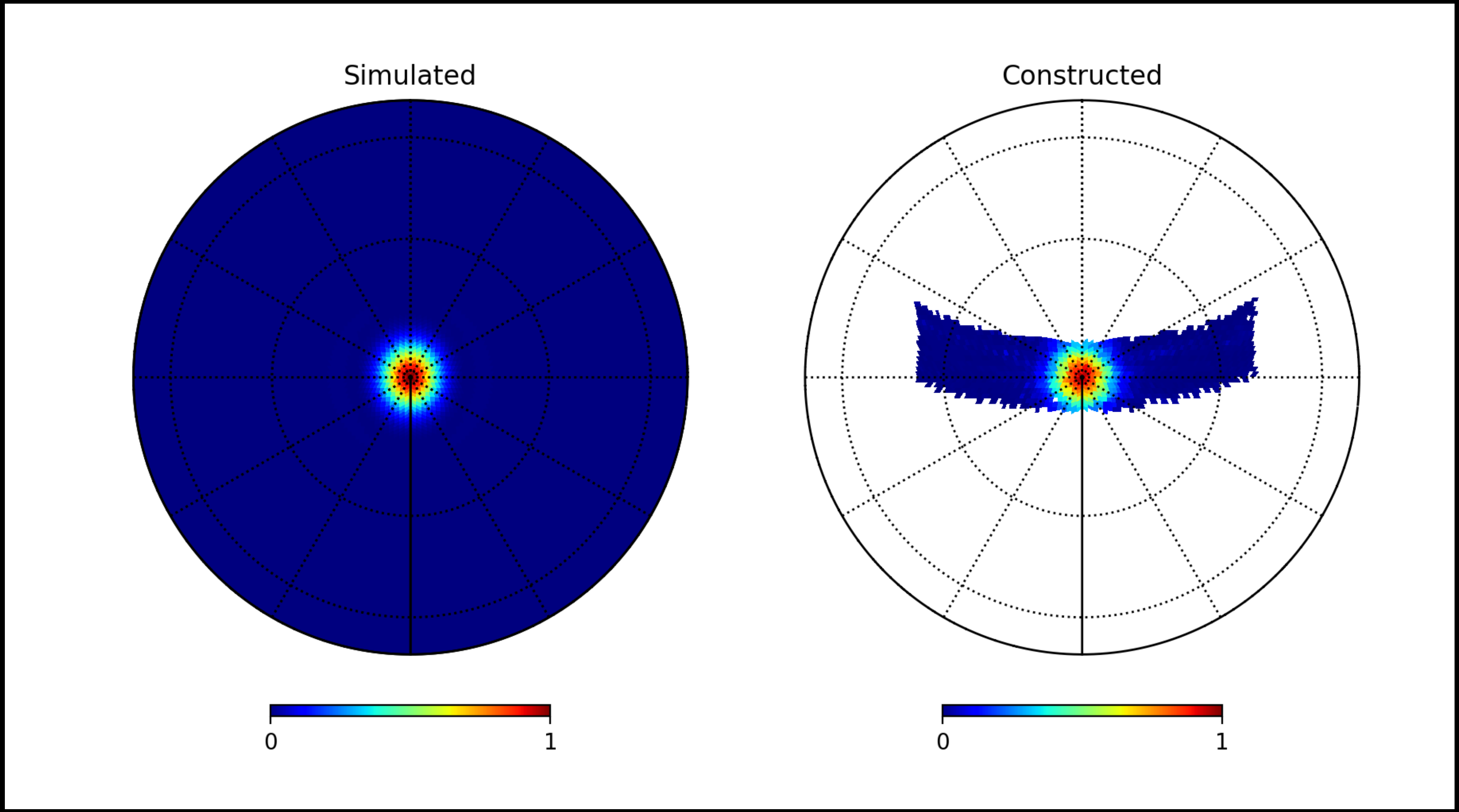
Ways we are trying to deal with spectral structure

1. Make sure our new signal path is “spectrally smooth”.

2. Make sure that the array is sufficiently redundant to avoid calibration errors.

3. Figure out ways to robustify redundant calibration against non-redundancy and sky-model incompleteness.

We are Determining redundancy of the beam using HERA observations



Reconstructed beam using astronomical source measurements from HERA observations

See the next talk by Chuneeta

We are also using drones.

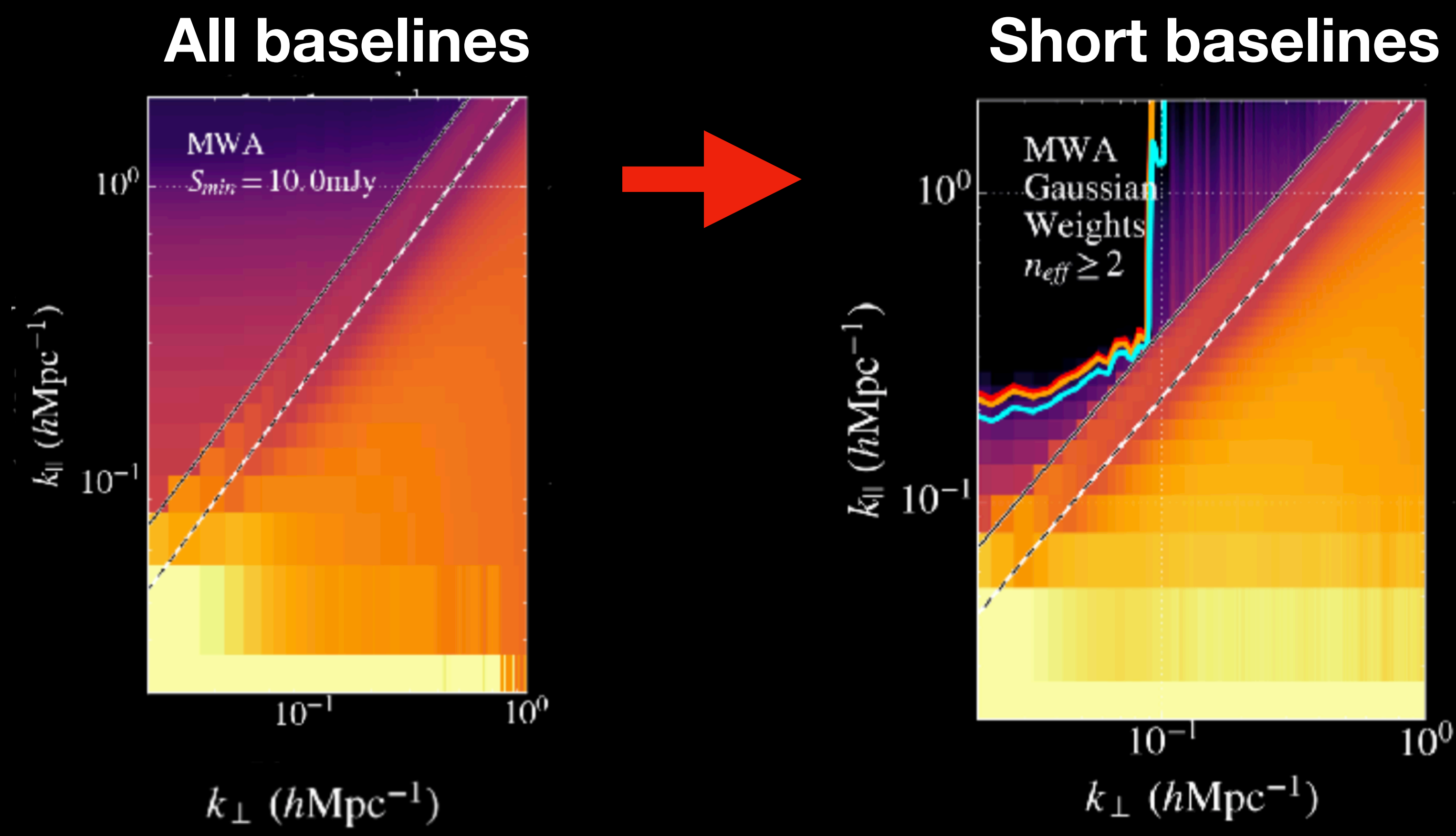
Ways we are trying to deal with spectral structure

1. Make sure our new signal path is “spectrally smooth”.

2. Make sure that the array is sufficiently redundant to avoid calibration errors.

3. Figure out ways to robustify redundant calibration against non-redundancy and sky-model incompleteness.

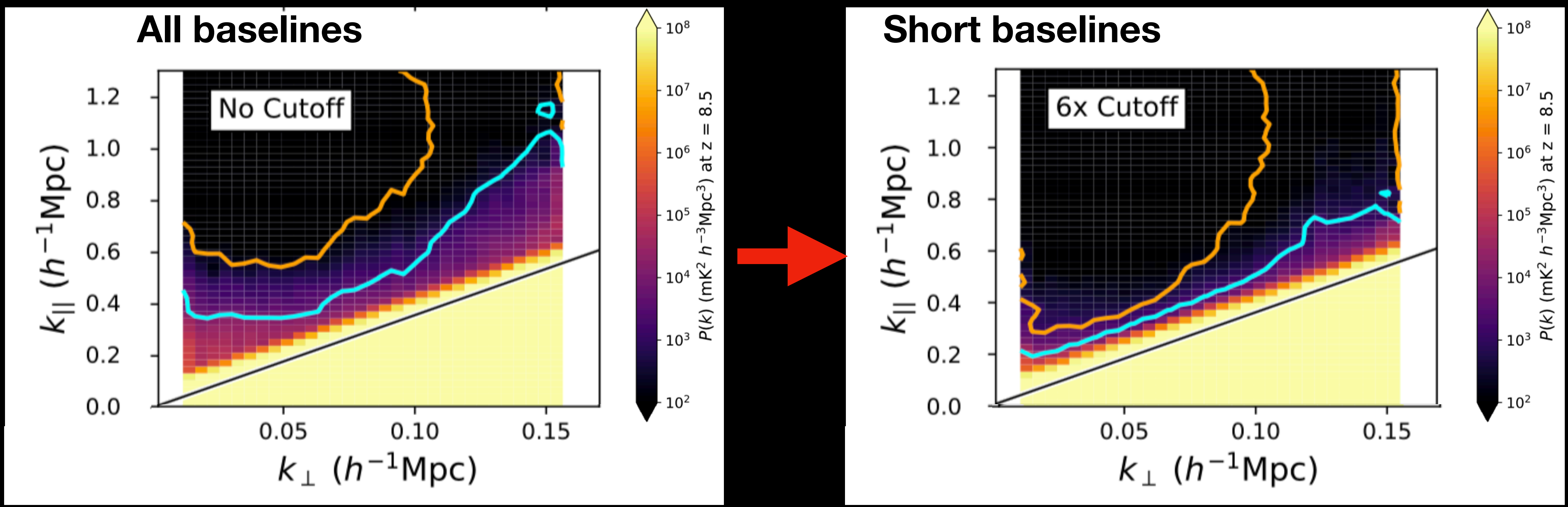
Calibrating with Short Baselines



AEW+ 2018

You'll Need A "Good enough" Diffuse Sky Model!

Orosz+ 2018



Summary

- HERA is happening!
  - Analysis nearing completion for 47 feeds with PAPER backend.
  - ~50 new signal chains (RFoF) and broad-band antennas will be operational in early Spring.
- All 21-cm instruments face the obstacle of spectral structure. In HERA, we are attacking the problem by:
  1. Making sure our Signal Chain is Smooth
  2. Ensuring Sufficient redundancy
  3. Improving calibration algorithms.